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A Review of the Effects of Dietary Restriction, Dehydration, and Caffeine Withdrawal on Cognition: Implications for a Disabled Submarine Scenario

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ABSTRACT

In the event that submariners become trapped aboard a disabled submarine (DISSUB), they must perform a multitude of cognitively demanding tasks in order to maximize their likelihood of survival. During this time, submariners will also be forced to endure poor living conditions, including drastic changes to their nutrition. These nutritional changes have the potential to impair submariners' cognitive functioning and affect operational performance, which could jeopardize survival; however, the effects of DISSUB nutrition on cognitive performance are not well understood. This review first describes the unique nutritional conditions that submariners will experience in a DISSUB scenario, including the change to a high-fat/low-calorie diet, restricted water availability, and cessation of caffeine consumption. The known effects of diet (including a high-fat diet and caloric restriction), dehydration, and caffeine withdrawal on cognition are then separately reviewed, with a discussion of how these effects may impact survivability in a DISSUB scenario.

Keywords: disabled submarine, nutrition, caffeine, dehydration, cognition, diet

Introduction

During operations, a submarine could experience an incident, such as flooding, collision with another vessel, system failure, or fire/explosion, which would render it unable to surface (Chabal et al., 2019; Harvey & Carson; 1989; Submarine Casualties Booklet, 1996; Whybourn et al., 2019). Since 1939, there have been 65 disabled submarine (DISSUB) scenarios, with the most recent being the loss of the ARA San Juan (S-42) in 2017 (Whybourn et al., 2019).[1] While there were no survivors from the ARA San Juan incident, a review of historical DISSUB events suggests that the majority of DISSUB scenarios (*ca* 80%) are survivable (Whybourn et al., 2019). In a survivable DISSUB scenario, submariners must survive either until rescue assets arrive (the preferred course of action) or escape becomes necessary due to worsening conditions. The period that submariners are confined within the DISSUB is referred to as the onboard survival phase and may last upwards of seven days (Department of the Navy, 2010; NAVSEA, 2013b).

Throughout the onboard survival phase of a DISSUB scenario, submariners will have to perform a multitude of mentally-demanding operational duties that involve a variety of cognitive domains: psychomotor function will be used when operating specialized survival and escape equipment; attention/vigilance will be required to continuously monitor the DISSUB environment for additional risks in order to respond quickly and appropriately; memory will be required to recall information from past training; mathematical processing will be used to calculate how long the DISSUB atmosphere will remain habitable; decision-making will be essential for assessing options and making risk-conscious decisions, including whether to initiate escape or await rescue; and mood will be strained as submariners attempt to maintain positive morale in a life-threatening situation (NAVSEA, 2013b). Impairment of any of these cognitive domains could slow submariners' ability to execute time-sensitive tasks or cause them to make errors that could gravely jeopardize their likelihood of survival. For example, a submariner with impaired mathematical processing may miscalculate the amount of time before oxygen becomes depleted, resulting in submariners endangering themselves by either initiating an escape prematurely and being exposed to unsafe surface conditions or by waiting too long and being exposed to unsafe atmospheric conditions (e.g., increased pressure and/or carbon dioxide levels).

[1] For a comprehensive overview and capability gap analysis of past DISSUB events, see Whybourn et al. (2019).

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Research has overwhelmingly shown that an individual's state of wellness affects his or her cognitive functioning (e.g., Banbury & Berry, 1998; Helton et al., 2011; Killgore, 2010). In a DISSUB scenario, the loss of power and other functional restrictions (Eckenhoff, 1980; NAVSEA, 2013b) will result in poor living conditions (Chabal et al., 2019; Whybourn et al., 2019), which has the potential to impair submariners' cognition. This cognitive impairment could negatively affect submariners' ability to carry out essential survival operations and decrease their likelihood of survival.

While there are many external factors during a DISSUB scenario that are likely to affect submariners' health and functioning (see Chabal et al., 2019 for a full discussion of the stressors expected to be present during a DISSUB event), most are completely outside the control of submarine crews faced with an emergent situation or of leadership planning for a potential DISSUB event (e.g., increased pressure, flooding, changes in atmospheric composition; see Chabal et al., 2019). Nutritional intake, however, is likely to be within the control of the crew, and can be readily influenced by modifying current guidance provided to submariners. It is therefore important to understand how the diet imposed on DISSUB survivors is likely to impact their cognition, so that countermeasures or policy changes can be put in place to ensure that survivors are functioning as optimally as possible.

Although definitions of nutrition vary (Beauman et al., 2005), here nutrition is defined as the intake of energy and nutrients necessary to establish and maintain function; this definition includes food, water, and other consumed substances, such as caffeine. All of these nutritional components alter the metabolic processes within the brain that generate the energy required to support cognitive functioning (Falkowska et al., 2015; Gómez-Pinilla, 2008; Kempton et al., 2010; Leonard & Robertson, 1992). Given the unique constraints of a submarine environment (e.g., lack of natural sunlight, limited mobility, long mission length, and limited food storage space), developing and providing optimal nutrition for submariners has long posed a challenge (Brown, 1942; Gilman et al., 1980; Korschevar, 1952; Sack et al., 1986; Shake & Schlichting, 1996). While current submarine nutrition practices are generally considered sufficient to support submariner health and functioning (e.g., Singh et al., 2011), the operational and logistical constraints of a DISSUB scenario will require submariners to drastically alter their nutritional intake (e.g., loss of refrigeration and cooking capabilities). The effects of these nutritional changes in a DISSUB scenario on submariners' cognition are generally not well understood.

In this review, several unique nutritional conditions that submariners will experience in a DISSUB scenario are described. These conditions are: a change to a high-fat/low-calorie diet, insufficient water intake to meet hydration demands, and cessation of caffeine consumption resulting in caffeine withdrawal. The known effects of diet (including a high-fat diet and caloric restriction), dehydration, and caffeine withdrawal on cognition are then separately reviewed, with a discussion of how these effects may impact survivability in a DISSUB scenario. To identify possible studies for this review, literature was compiled from searches of Google Scholar, Google browser, PubMed, the Defense Technical Information Center, and the archive of Technical Reports from the Naval Submarine Medical Research Laboratory.

Nutrition During a DISSUB Scenario

Change to High-Fat, Low-Calorie Diet

One of the most significant threats to survival in a DISSUB scenario is the uncontrolled rise in carbon dioxide (CO_2) levels (Harvey & Carson, 1989; Chabal et al., 2019; NAVSEA, 2013a, 2013b; Whybourn et al., 2019). Each submariner produces approximately 22.3 L/hr of CO_2 (Gunner et al., 2018). Multiple countermeasures are used in a DISSUB scenario to minimize the amount of CO_2 produced by each individual, including a drastic change in diet. Current U.S. Navy (NAVSEA, 2013b) and North Atlantic Treaty Organization (NATO, 2015) DISSUB procedures require submariners to decrease the volume of food consumed in order to reduce metabolic production of CO_2. While neither NATO nor the United States prescribes specific caloric limits, U.S. guidelines state that *"the amount of food eaten by each survivor should be restricted so that they remain hungry (but not starving)"* (NAVSEA, 2013b). Following this guideline, laboratory DISSUB simulations have provided participants a range of 1100–2000 kcal/day (Francis et al., 2002; Risberg et al., 2004). Overall, this diet is likely to result in submariners running a caloric deficit, as previous research on Indian submariners found an average caloric consumption of approximately 3518 kcal/day over a three-month period of normal submarine operations (Singh et al., 2011). Exact energy demands and the amount of caloric deficit experienced will vary based on the DISSUB conditions (e.g., ambient temperature) and individual metabolic needs (Gunner et al., 2018; NATO, 2015).

In addition to the DISSUB diet being calorically limited, DISSUB procedures dictate that the diet should have a macronutrient composition that is high in fat and low in carbohydrates (NATO, 2015), with U.S. submariners prioritizing the consumption of high-fat foods (NAVSEA, 2013b). Fats are the preferred macronutrient because they are a more calorically-dense form of energy (9.3 kcal/g of fat) compared to carbohydrates (4.3 kcal/g) or proteins (4.2 kcal/g) (Widdowson, 1955). Therefore, a diet consisting primarily of high-fat foods will provide the desired amount of calories while reducing the volume of food that must be digested; this will further reduce the amount of

CO_2 that submariners metabolically generate (McCarter et al., 1985). Cooking will not be possible in a DISSUB scenario; while some countries such as the United Kingdom provide specific emergency food rations for a DISSUB event (Whybourn et al., 2019), U.S. submariners must subsist off of foods such as cold cuts, nuts, and ice cream (NAVSEA, 2013b).

Insufficient Water

Water comprises approximately 60% of the body mass of healthy young adults and is essential for supporting the physiological processes vital for life (Jéquier & Constant, 2010; Kleiner, 1999; Thomas & O'Brien, 2008). Throughout the day, the body loses water as a result of respiration, perspiration, and waste excretion, and dehydration occurs when water intake is insufficient to replenish the water that is lost through these processes.

There are multiple factors that may contribute to submariners becoming dehydrated in a DISSUB scenario. One factor is that the temperature and humidity are expected to progressively increase throughout the course of a DISSUB scenario due to a lack of climate control capabilities and the high thermal insulator properties of modern submarine hulls (Berglund et al., 2013; Chabal et al., 2019; Horn et al., 2009). This will result in substantial body water loss from perspiration, with the degree of loss varying based on external heat, humidity, and activity level. Under thermoneutral sedentary conditions, water lost through sweat is approximately 0.3 L/hr; however, sweat output can increase to 2 L/hr when individuals are exposed to extreme heat (Popkin et al., 2010; Sawka et al., 2008). The likely increase in temperature during a DISSUB scenario will render submariners highly susceptible to dehydration from increased sweat output.

The stress of a DISSUB scenario may also cause dehydration among submariners. Periods of acute stress can incite increased sweating (Bracha et al., 2004). Furthermore, stress may cause some submariners to neglect their thirst response (Herman et al., 1987). To replace water loss and prevent dehydration, the body incites a desire to drink (i.e., regulatory thirst) in the individual through a complex system of physiological triggers (Bourque et al., 1994). Although there is controversy over whether regulatory thirst is adequate for maintaining euhydration (Armstrong et al., 2016; Hoffman et al., 2016), evidence suggests that satiating thirst is generally sufficient for young, healthy individuals at rest (as is representative of submariners in a DISSUB scenario; Casa et al., 2005). However, previous research has indicated that stress can alter the way that individuals respond to satiety. When exposed to stress, some individuals neglect natural feelings of satiety and subsequently do not consume enough to fulfill their bodily needs (Herman et al., 1987; Kivimäki et al., 2006). To compensate for this, U.S. DISSUB procedures state that *"a designated individual should be given the responsibility of ensuring that each survivor consumes adequate quantities of fluid"* (NAVSEA, 2013b), with NATO regulations suggesting a minimum intake of one liter per day per survivor (NATO, 2015).

Another factor that may lead to dehydration among submariners in a DISSUB scenario is that water intake via food consumption will be limited. A U.S. survey estimated that approximately 20% of water intake comes from food sources (Ershow & Cantor, 1989), with fresh fruits and vegetables providing the highest water content (Altman & Katz, 1961). In a DISSUB scenario, the volume of food consumed is limited, and the high-fat foods that are prioritized for consumption (e.g., nuts, cheeses, and meats) are generally lower in water content (NAVSEA, 2013b). Both of these factors will likely limit the water that submariners receive via food. While limited water intake from food sources may not be a primary cause of dehydration in a DISSUB scenario, it may have a meaningful impact in heat-exposed submariners who are more predisposed to dehydration (Horn et al., 2009).

Cessation of Caffeine Consumption

Caffeine consumption is widespread in the military as a means of mitigating fatigue and is typically consumed as a component of coffee, tea, soft drinks, and energy drinks (Cohen et al., 2013; Gilbert, 1984; Stephens et al., 2014; Toblin, 2018; Waits et al., 2014). In a survey of caffeine consumption among active duty U.S. Navy personnel, 87% of servicemen reported regular caffeine consumption, with an average consumption of 232 mg/day (Knapik et al., 2016). This average daily consumption is slightly higher than the average for adult U.S. men (average daily consumption approximately 196-211 mg/day; Ahuja et al., 2006; Frary et al., 2005; Fulgoni et al., 2015; Mitchell et al., 2014). Notably, caffeine consumption among U.S. Navy service members is associated with age and rank, such that older, more senior service members consume more caffeine on average than younger, more junior service members (Knapik et al., 2016; Stephens et al., 2014). While survey-based research has not yet explored caffeine use specifically among U.S. submariners, there is no evidence to suggest that caffeine use among submariners would be lower than that of general U.S. Navy service members. Conversely, one could expect submariners to consume more caffeine to counter the effects of fatigue caused by their demanding watchbills, lack of exposure to natural light, and constant boat motion (Chabal et al., 2018); however, this remains to be studied. Overall, it can be expected that regular caffeine consumption in the submariner population is prevalent and that average daily consumption is relatively high (more than 200 mg/day, the equivalent of approximately three 8 oz. cups of brewed coffee; Knight et al., 2004).

In a DISSUB scenario, caffeine sources are likely to be highly limited or completely unavailable. Normal kitchen operations are suspended, and caffeinated beverages (i.e., the primary source of caffeine among U.S. Navy personnel; Knapik et al., 2016) will not be available (NAVSEA, 2013b). Current information from the Navy Assemblage Information Logistics System indicates that caffeine pills are not stocked anywhere on a U.S. submarine (Pilmanis et al., 2016). Though submariners may have a personal supply of carbonated drinks containing caffeine (e.g., cola-type sodas, energy drinks, etc.), carbonated drinks are not to be used during a DISSUB because they are pressurized with CO_2 (NAVSEA, 2013b). While hot coffee will not be brewed, it is possible that submariners may mix coffee grounds with what water they have available or "chew" the grounds in order to consume caffeine. This is not specifically recommended in U.S. DISSUB instructions, and submariners may fail to think of it; however, this may be the only means of alleviating caffeine withdrawal among caffeine-habituated submariners.

Due to the psychoactive nature of caffeine, it produces physical dependence following chronic use, and habituated individuals experience physiological withdrawal when caffeine is no longer consumed (Strain et al., 1994). The incidence and severity of the effects of caffeine withdrawal vary based on how much caffeine one typically consumes; however, research suggests that individuals who typically consume as little as 100 mg/day may experience withdrawal symptoms following cessation (Evans & Griffiths, 1999; Griffiths et al., 1990). Given the prevalence of caffeine use among submariners, caffeine withdrawal could be rampant in a DISSUB scenario.

Cognitive Effects of DISSUB Nutrition

Diet

The DISSUB diet is unique in that it is a low-calorie and high-fat diet. These diet characteristics may affect cognition independently and are therefore reviewed separately. To the author's knowledge, no one has reviewed the cognitive effects of a combined low-calorie and high-fat diet similar to what submariners would consume in a DISSUB scenario.

Caloric restriction

Many studies have sought to characterize the effects of caloric restriction (primarily during periods of fasting) on cognition; however, results remain equivocal (for reviews, see Feldman & Barshi, 2007; Galioto & Spitznagel, 2016). Some studies have observed impairments in attention, executive function, motor control, and memory following short-term fasting, such as skipping a meal (e.g., Benton & Parker, 1998; Bolton et al., 2014; Pender et al., 2014). On the other hand, approximately as many studies have failed to find any effects of short-term fasting in those same cognitive domains, despite testing moderate to large sample sizes (30–60 participants; Sünram-Lea et al., 2001; Yasin et al., 2013). In general, the greater the caloric restriction or the longer the duration of the fast, the more likely a study is to observe cognitive impairment. For example, Tian et al. (2011) observed short-term memory deficits after ten hours of fasting, but not after only three hours of fasting. Research suggests that, despite changes in blood and interstitial glucose levels, the brain's glucose supply is held relatively constant via glucose transporters unique to the brain (Simpson et al., 2008). Only when blood glucose levels drop to approximately 49 mg/dL is glucose supply to the brain restricted sufficiently to cause declines in cognitive function (Mitrakou et al., 1991). This potentially reflects an evolutionary advantage of maintaining cognitive functioning despite short-term changes in food availability (Maille & Schradin, 2017), and cognitive deficits may only arise following extended periods of caloric restriction. However, the duration of fasting period does not wholly account for the variance of results across studies; some studies have not observed any evidence of cognitive impairments even after several days of near-total caloric restriction (e.g., Lieberman et al., 2008).

Various methodological differences across studies may account for these discrepant results. Numerous studies observe the effects of caloric restriction during periods of religious fasting, such as during Ramadan or the Tenth of Tevet (e.g., Doniger et al., 2006; Yasin et al., 2013). Other studies instruct participants to skip meal(s) before coming into the laboratory for testing (e.g., Green et al., 1995, 1997). Both of these study approaches lack participant blinding; thus, participant expectations may affect results (e.g., Jadad et al., 1996). Popular claims that skipping meals has negative cognitive consequences can influence participants' perception and their subsequent performance on cognitive assessments (e.g., Jadad et al., 1996). To address this, some studies have implemented participant blinding by having participants consume glucose drinks or hydrocolloid gels with varying caloric content and/or macronutrient composition. For example, Lieberman et al. (2008) investigated the effects of two-day caloric restriction on cognitive functioning and mood by providing participants with gels providing either 2294 kcal (control condition) or 313 kcal (caloric-restriction condition). The authors found no significant differences between the conditions on measures of vigilance, reaction time, learning, memory, reasoning, or mood, suggesting no effects of short-term caloric restriction on cognitive functioning. This was true despite observing lower interstitial glucose concentrations and lower perceived satiety during the caloric-restriction condition (Lieberman et al., 2008). This scenario is likely a more extreme caloric restriction than would be experienced on a DISSUB (313 kcal/day vs. *ca* 1100–2000 kcal/day); however, a DISSUB scenario may persist for up to seven days (compared to two days in the Lieberman et al., 2008 study).

Another issue posed by lack of participant blinding is that participants may alter their food consumption patterns leading up to the caloric restriction. Namely, participants may consume additional food prior to fasting in order to "stock up" on energy (e.g., Ziaee et al., 2006). This uncontrolled pre-study behavior may alter the condition that the body is in prior to the caloric restriction (e.g., increased fat and glycogen stores to draw from), potentially minimizing the effect of short-term caloric restriction on cognition. Submariners in a DISSUB scenario will not have much warning. Therefore, they will not have the opportunity to prepare their bodies for the forthcoming caloric restriction. This may make cognitive deficits more likely to occur or cause them to develop more rapidly and/or magnify them.

Different fasting procedures may also produce varied results. Some studies conduct fasting with total food and fluid restriction (e.g., Doniger et al., 2006), whereas other studies allow individuals to drink calorie-free beverages freely (e.g., Green et al., 1995). In studies using the former method, observed declines in cognition may be the result of the effects of dehydration or the interaction between caloric restriction and dehydration. In a DISSUB scenario, participants may simultaneously experience caloric restriction and dehydration.

Participant activity levels during fasting will also modulate the effects of caloric restriction on cognition (Maille & Schradin, 2017). Physical activity represents a competing source of energy expenditure and may cause cognitive deficits to develop more rapidly or to a greater extent during times of caloric restriction (Giles et al., 2019). In some studies, participants go about their regular routines while fasting (Pender et al., 2014; Yasin et al., 2013); other studies investigate the effects of fasting under periods of high physical activity such as athletic or military training (Landers et al., 2001; Tian et al., 2011). Neither of these situations is representative of individuals in a DISSUB scenario, in which physical activity is strictly limited in order to minimize respiratory and metabolic demands (Chabal et al., 2019; NAVSEA, 2013b). The effects of caloric restriction on cognition when individuals are performing only minimal activity warrant further research (for a recent review, see Cherif et al., 2016).

Overall, the effects of caloric restriction on cognition are highly variable, and the effects of caloric restriction under DISSUB-like conditions are not well understood. The vast majority of studies examine effects of caloric restriction in the short term (e.g., from skipping a single meal up to a day or two; Doniger et al., 2006). As a DISSUB scenario may extend upwards of seven days, the effects of longer periods of caloric restriction are of considerable operational relevance. Some long-term studies have found cognitive improvements in elderly or overweight participants enrolled in caloric restriction diets lasting months to years (Gillette-Guyonnet & Vellas, 2008; Smith et al., 2010; Witte et al., 2009); however, it is not appropriate to generalize these results to submariners in a DISSUB scenario due to differences in duration of diet adherence and participant characteristics. Future research examining the cognitive effects of multi-day, partial caloric restriction is warranted.

High-fat diet

Large-scale cross-sectional studies have associated long-term adherence to high-fat diets with increased prevalence of cognitive impairment and decline (Eskelinen, 2008; Solfrizzi et al., 2003). While the correlational nature of this association precludes the drawing of causal conclusions, recent experimental research has indicated that even short-term adherence (i.e., four to seven days) to high-fat diets may impair cognitive functioning (Holloway et al., 2011). Rodent studies have indicated that a high-fat diet impairs hippocampal-dependent processes including memory and learning (for a recent review, see Cordner & Tamashiro, 2015). These findings are supported by human subject studies in which the speed of memory recall and/or accuracy of recall are impaired. Holloway et al. (2011) subjected participants to a diet in which 70% of calories came from fat. After five days, participants presented with impaired attention and processing speed of memory recall, though accuracy of memory recall was unaffected. Similarly, other researchers have identified impairments in hippocampal-dependent memory processes following acute high-fat diet consumption (Attuquayefio et al., 2017; D'Anci et al., 2009b; Edwards et al., 2011).

Multiple mechanisms have been proposed to explain the impairing effects of a high-fat diet on cognitive functioning. Several studies have proposed that high-fat diets cause increased free fatty acid density in the body, resulting in oxidative stress in the brain (e.g., Xia et al., 2015). Another potential mechanism is that glucose regulation becomes impaired causing insufficient glucose transportation to the brain (Cordner & Tamashiro, 2015). Because glucose is an essential energy source for supporting cognitive processes (DeCarli et al., 1995; Gold, 1995), insufficient glucose delivery may impair cognitive functioning. Another proposed mechanism is that alterations to synaptic plasticity obstruct the hippocampal mechanisms necessary for memory and learning processes (e.g., Arnold et al., 2014). Further research is required to delineate the neurobiological mechanism(s) involved.

Despite these findings, a high-fat diet may improve cognition under certain contexts in hyperbaric and undersea medicine. Studies have found that individuals experiencing nutritional ketosis—a metabolic state in which a high-fat/low-carbohydrate diet causes the body to derive energy primarily from fat (Rho & Stafstrom, 2012; Zhao et al., 2017)—are more resilient to cognitive deficits caused by hypoxia (Zhao et al., 2017) and oxygen toxicity (D'Agostino et al., 2019). Because submariners are at risk of developing either hypoxia or oxygen toxicity depending on the conditions of a DISSUB scenario (Chabal et al., 2019; Whybourn et al., 2019), a high-fat diet may enhance submariners' performance by providing ketogenic cognitive resilience (Rho & Stafstrom, 2012). However, entering nutritional ketosis is a process requiring multiple days of adherence to a high-fat/low-carbohydrate diet (Harvey et al., 2018), and submariners will have to have already entered nutritional ketosis at the time of developing hypoxia or oxygen toxicity in order to garner any protective effect. Given that the DISSUB diet is of both low calorie and high fat, the rate at which nutritional ketosis would develop (if it develops at all) under a DISSUB diet is not known.

Overall, there is limited but consistent evidence to suggest that a high-fat diet will impair submariner cognition in a DISSUB scenario. Specifically, memory and learning processes are likely to be affected (Attuquayefio et al., 2017; Edwards et al., 2011), which could jeopardize survival by impairing submariners' ability to recall information from previous trainings or learn how to operate escape equipment with which they may not have prior experience.

Dehydration

Ample evidence establishes that dehydration has a deleterious effect on cognition (e.g., Cian et al., 2000; Ganio et al., 2011; Grandjean & Grandjean, 2007). However, the severity of dehydration at which cognition is impaired and the specific cognitive domains that are affected are not definitively known (Adan, 2012; Benton, 2011; Masento et al., 2014). Researchers have hypothesized multiple neurobiological mechanisms by which dehydration affects cognitive functioning (Fadda et al., 2012; Faraco et al., 2014; Gross et al., 1985). Animal studies have observed alterations in glucose utilization in dehydrated rats, suggesting that cognitive deficits may be the result of depressed metabolic activity in the forebrain (Gross et al., 1985). Other studies have observed that dehydration induces oxidative stress, leading to cerebrovascular dysregulation, which may drive cognitive impairments (Fadda et al., 2012; Faraco et al., 2014). Dehydration has also been associated with increased cortisol levels, which may have negative effects on cognitive functioning (Kirschbaum et al., 1996). See Adan (2012) for a comprehensive review of the neurobiological bases of dehydration.

Numerous studies have observed decreases in reaction time accuracy and/or increases in reaction time latency when individuals are dehydrated (Baker et al., 2007; Cian et al., 2001; Ganio et al., 2011). There is evidence that these deficits begin at mild degrees of dehydration (1–2% of mass lost through body water; D'Anci et al., 2009a). However, other studies have observed no effect of even moderate dehydration (2–5% mass loss) on performance during reaction time tasks (Serwah & Marino, 2006; Szinnai et al., 2005), and at least one study has observed improvements in reaction time during dehydration (Falcone et al., 2017).

Studies on the effects of dehydration on short-term memory have found similarly inconsistent results. Gopinathan et al. (1988) used a word recall task and observed progressive declines in short-term memory beginning at 2% dehydration, which is consistent with the deficits seen in other studies at similar degrees of dehydration (Cian et al., 2001; Patel et al., 2007). In contrast, other studies have found no effect (D'Anci et al., 2009a) or sometimes even an improvement in short-term memory performance when dehydrated (Tomporowski et al., 2007).

Research on working memory has been more consistent in its findings. Sharma et al. (1986) observed that performance on a working memory task became significantly impaired relative to baseline when individuals were 2–3% dehydrated but not when they were 1% dehydrated. Additionally, the effect was larger at 3% dehydration than at 2%, suggesting that deficits in working memory may be proportional to the degree of dehydration. Deficits in a spatial working memory task were also observed by Ganio et al. (2011) in individuals who were dehydrated to approximately 1.5% weight lost.

Other cognitive domains have not been researched as extensively as reaction time, short-term memory, and working memory. There have been no effects of moderate dehydration (2–5%) observed on executive function, processing speed, or inhibition (Falcone et al., 2017; Szinnai et al., 2005; Tomporowski et al., 2007). To the author's knowledge, no studies have investigated effects of dehydration on impulsivity or risk-taking behaviors.

Several reasons for the discrepant results across dehydration studies have been proposed. For example, multiple studies have suggested that some of the cognitive effects of dehydration may be masked by compensatory mechanisms. Kempton et al. (2010) observed greater neuronal activity in fronto-parietal brain regions during cognitive tests when individuals were dehydrated than in euhydrated control conditions; but this increased activity was not associated with differences in performance on the cognitive tests. The authors suggested that the increased neuronal activity indicated that individuals may have been expending greater effort on the tasks when they were dehydrated and were thus able to maintain performance. This hypothesis is supported by studies assessing participant mood. Multiple studies have observed that, although dehydrated performance was not significantly lower compared to baseline, participants reported decreased vigor, clearheadedness, and alertness, as well as increased fatigue and task-related effort when dehydrated (Baker et al., 2007; Cian et al., 2000; Ganio et al., 2011; Patel et al., 2007; Pross et al., 2014; Szinnai et al., 2005). These results suggest that, while individuals may have experienced cognitive deficits due to dehydration, they were able to compensate in the short term through increased effort expenditure.

In further support of the hypothesis that compensatory mechanisms mask cognitive decrements attributed to dehydration, multiple studies have observed declines in performance over the duration of extended cognitive tasks (Baker et al., 2007; D'Anci et al., 2009a). D'Anci et al. (2009a) separated performance on a fifteen-minute vigilance test into five-minute intervals and found that reaction times were stable across the test intervals when participants were euhydrated; however, reaction times increased over subsequent test intervals in the dehydration condition. These results suggest that participants may have been able to compensate in the early stages of the task, but this compensatory mechanism began to fail as the task progressed, and cognitive deficits began to emerge in task performance.

Another potential reason for the discrepant results of previous studies is the varied methodologies used to cause dehydration. Common methods of inducing dehydration include exposure to heat, prolonged exercise, diuretics, passively waiting for individuals to become dehydrated, and various combinations of the above (Lieberman, 2012). Different methods of eliciting dehydration may create different neurobiological profiles that will impact cognition in different ways. For example, exercise stimulates glutamatergic activity within the central nervous system, which may facilitate certain cognitive processes (Benton, 2011; Davranche et al., 2006; Maughan et al., 2007). This could be the reason that Tomporowski et al. (2007) observed an improvement in short-term memory performance when it was measured immediately following exercise. In this instance, it is possible that the beneficial effects of exercise on cognition (Tomporowski, 2003) masked any detrimental effects of dehydration that may have been present.

Previous authors have commented on the complication of comparing across research studies that induced dehydration in different ways because of the potential interactions involved (Benton, 2011; Lieberman, 2012). In partial examination of this issue, Cian et al. (2000) dehydrated individuals up to 2.8% body mass loss using either passive heat stress or aerobic exercise and then measured long-term memory, perceptive discrimination, short-term memory, reaction time, psychomotor function, and subjective mood. They found that both dehydration methods impaired short-term memory, perceptive discrimination, and subjective mood; however, there were no meaningful differences in cognitive functioning between the two dehydration methods, suggesting that the source of dehydration does not differentially impact cognition (Cian et al., 2000). However, while no measurable differences were found between dehydration methods measured acutely in these specific cognitive domains, it remains possible that performance differences would have emerged in the long term and/or would be evident in other cognitive measures.

As noted, the majority of research exploring the cognitive effects of dehydration has explored acute exposure (e.g., Falcone et al., 2017; Szinnai et al., 2005; Tomporowski et al., 2007). It is not well understood how long-term dehydration might impact cognitive performance, or whether any of the potential compensatory mechanisms used to mitigate difficulties in acute conditions (Kempton et al., 2010) are sustainable for longer periods. Submariners in a DISSUB scenario are likely to experience longer-term dehydration lasting up to seven days, and the effects of this multi-day dehydration are not well known. In a longer-term dehydration study, Lindseth et al. (2013) enrolled pilots in multi-week diet plans providing either high-fluid or low-fluid intakes. At the end of each diet plan, participants completed a full-motion flight simulator. Results showed significantly poorer flight performance for dehydrated pilots compared to euhydrated pilots, suggesting that compensatory mechanism(s) may not have been sufficient to overcome chronic deficits. However, that study examined the effects of dehydration over several weeks, so it is not known how the results may translate to a DISSUB scenario lasting for multiple days.

While it is possible that dehydration may impair the cognitive functioning of submariners in a DISSUB scenario, the specific cognitive domains that are likely to be affected by chronic dehydration are not well known. It has been suggested that rehydration can rapidly restore cognitive performance; however, the manner and time course at which rehydration may alleviate cognitive dysfunction are relatively unexplored. When research does exist, it has focused primarily on rehydration following exercise-induced dehydration (e.g., Bandelow et al., 2010; Choma et al., 1998; Masento et al., 2014; Wong et al., 2014) rather than following passive heat exposure, as would be more typical of a DISSUB scenario. This may be important if the mechanisms by which rehydration restores cognitive function differ depending on the cause of dehydration (Lieberman, 2010). To circumvent this, maintaining adequate hydration should be a priority in a DISSUB scenario. In addition to the designation of an individual tasked with keeping survivors hydrated (NAVSEA, 2013b), submariners should pay attention to their urine color, which is generally a valid and sensitive field measure of overall hydration status (Armstrong et al., 1994, 1998).

Caffeine Withdrawal

There are a number of studies exploring the putative benefits of acute caffeine consumption on cognition, with some studies identifying a benefit (e.g., Brice & Smith, 2001; Smith et al., 2006), and others not (e.g., Loke, 1988; Mednick et al., 2008). In those studies that have found a benefit of caffeine, there is considerable debate as to whether this benefit is truly an improvement caused by the stimulant properties of caffeine or merely a reversal of negative withdrawal symptoms (Christopher et al., 2005; James & Rogers, 2005; Rees et al., 1999; Smith et al., 2002; Yeomans et al., 2002). This debate is outside the scope of the present review. Instead, this review focuses on the literature exploring the deleterious effects of caffeine withdrawal on individuals, as that is most relevant for a DISSUB scenario. The following paragraphs discuss the effects of caffeine withdrawal on subjective mood, subjective cognitive functioning, and objective cognitive measures.

Caffeine withdrawal has a number of negative effects on subjective ratings of mood in individuals. Following caffeine cessation, individuals report higher levels of fatigue, drowsiness, and irritability, as well as decreased friendliness and amicability compared to baseline (Griffiths et al., 1990; Juliano & Griffiths, 2004; Keane et al., 2007; Lane & Phillips-Bute, 1998; Mills et al., 2016; Rogers et al., 2013; Sigmon et al., 2009; Silverman et al., 1992). The degree of these mood changes is typically associated with the magnitude of caffeine dependence prior to cessation (Juliano & Griffiths, 2004). That is, individuals who have greater daily caffeine intake typically experience more negative changes to mood following caffeine cessation than individuals with lower levels of daily caffeine intake (Evans & Griffiths, 1999; Silverman et al., 1992). Several physiology studies have sought to characterize the underlying mechanism of these subjective changes. It has been hypothesized that increases in cortical theta oscillations (neural oscillatory patterns from 4 to 7 Hz) following caffeine cessation may be the cause (Jones et al., 2000), as increased theta activity is associated with drowsiness (Makeig & Jung, 1995). However, theta activity has also been observed to increase when individuals consume caffeine (Sigmon et al., 2009), suggesting that increases in theta activity following caffeine cessation may reflect a general change in body caffeine level, rather than the physiological underpinning of withdrawal effects on mood (Sigmon et al., 2009).

Caffeine withdrawal has also been shown to negatively affect self-report ratings of cognitive functioning. Individuals experiencing caffeine withdrawal report decreases in mental alertness, ability to concentrate, clearheadedness, and vigor, as well as increased perceived difficulty when performing cognitively-demanding tasks (Jones et al., 2000; Juliano & Griffiths, 2004; Keane et al., 2007; Lane & Phillips-Bute, 1998; Rogers et al., 2005; Silverman et al., 1992). These symptoms are reliably reported when participants are administered a placebo under double-blind conditions and even when participants are deceptively told they have consumed caffeine when they actually have not (Mills et al., 2016). The magnitude of these self-report symptoms is proportional to the amount of caffeine intake prior to cessation, with greater caffeine intake associated with more severe changes in subjective state (Evans & Griffiths, 1999; Juliano & Griffiths, 2004; Rogers et al., 1995, 2013; Silverman et al., 1992).

There is strong evidence that caffeine withdrawal degrades sustained attention (Juliano & Griffiths, 2004). Caffeine-withdrawn individuals typically exhibit increased reaction times on both simple and complex tasks, and decreased accuracy on complex attention tasks compared to baseline performance (Rogers et al., 2005; Yeomans et al., 2002). Furthermore, withdrawn individuals' performance degrades more rapidly over the duration of a vigilance task, suggesting they are more susceptible to time-on-task fatigue (Lane & Phillips-Bute; 1992; Rogers et al., 2013). The magnitude of performance degradation on sustained attention tasks is proportional to caffeine dose (Rogers et al., 2013; Silverman et al., 1992). While there are still some studies that have shown no effects of caffeine withdrawal on sustained attention, the results of those studies are likely due to methodological choices, such as only analyzing accuracy when performance was near ceiling (Keane et al., 2007) or using a between-subjects design that may be less sensitive to the effects of withdrawal (Rogers et al., 2005). Overall, the objective cognitive results reported in the literature are consistent with the self-report profile that individuals feel less clearheaded and attentive when caffeine-withdrawn.

Other objective cognitive measures have been less studied in relation to caffeine withdrawal. Rogers et al. (2013) examined the effects of caffeine withdrawal on a memory recognition task and found that individuals experiencing caffeine withdrawal performed significantly poorer when required to remember changing sets of information. However, other studies have found no evidence for memory impairments during caffeine withdrawal using memory tasks such as simple word recall (Jones et al., 2000; Rogers et al., 2005). Taken together, these results suggest that caffeine withdrawal may not impair simple memory recall, but it may disrupt the ability to correctly retain and update information; however, further research is required.

With respect to other cognitive domains, at least one study has shown impairments in linguistic processing of complex syntax following caffeine cessation (Rogers et al., 2005), and Streufert et al. (1995) observed impairments in abstract complex thinking associated with caffeine withdrawal; however, Lyvers et al. (2004) found no such difference in complex thinking when using a between-subjects design. Overall, further research is required to validate the effects of caffeine withdrawal on cognitive domains other than sustained attention/vigilance.

One area that has not been explored is how caffeine withdrawal may affect impulsivity and propensity towards risk-taking. This has high operational relevance in a DISSUB scenario, as submariners will be making critical survival decisions (i.e., initiating escape vs. awaiting rescue), and risk should be minimized. There is theoretical reasoning to suggest that impulsivity and risk-taking propensity may be exacerbated in individuals experiencing caffeine withdrawal. Caffeine dependence is associated with higher trait measures of impulsivity in men (Jones & Lejuez, 2005; Waldeck & Miller, 1997), and the combined stress of the DISSUB scenario and caffeine withdrawal may further bring out this heightened impulsivity (Lejuez et al., 2002; Lighthall et al., 2009). The effect of caffeine withdrawal on risk-taking propensity and impulsivity is an important one because caffeine consumption is highest among senior Navy service members (Knapik et al., 2016), who would be the most likely to act in a leadership role during a DISSUB scenario. Thus, those individuals with the most decision-making responsibility will also be most likely to experience caffeine withdrawal. For these reasons, future research should consider the effects of caffeine withdrawal on impulsivity and risk-taking behaviors.

Caffeine withdrawal is associated with a number of cognitive domains that have the potential to disrupt crew functioning during a DISSUB scenario. For example, decreases in clearheadedness and the ability to concentrate (e.g., Silverman et al., 1992) may disrupt individuals' ability to effectively follow complicated and unfamiliar escape procedures; decreases in friendliness and amicability (e.g., Lane & Phillips-Bute, 1998) may contribute to breakdown in command among submariners; and decreases in mental alertness and sustained attention (e.g., Rogers et al., 2005) may disrupt the submariners' ability to respond quickly and appropriately to changes in conditions that could motivate a change in action plan (e.g., CO_2 levels increase, and the crew should initiate an escape rather than wait for rescue). Studies have shown that some of the effects of caffeine withdrawal can be rapidly reversed within an hour of re-administering caffeine (Goldstein et al., 1969); however, the exact relationship between caffeine re-administration dose and alleviation of caffeine withdrawal symptoms warrants further research. Nevertheless, in a DISSUB scenario it may be important to prioritize the allocation of caffeine rations to individuals performing the most cognitively-demanding tasks in order to optimize their performance.

Summary and Conclusions

The present paper provided an overview of how submariners' nutrition will be affected in a DISSUB scenario and how those nutritional changes may affect their cognitive functioning. The primary nutritional changes discussed were a change to a high-fat/low-calorie diet, dehydration from insufficient water intake to meet hydration demands, and cessation of caffeine consumption resulting in caffeine withdrawal. Based on the literature reviewed, each of these nutritional changes has the potential to negatively affect cognition; though few studies have been conducted under conditions that are truly representative of a DISSUB scenario (e.g., exposure up to seven days, minimal participant physical activity, etc.). Further research under more DISSUB-like conditions is warranted to more precisely determine the affected cognitive domains (e.g., attention, memory, etc.), time course of deficit development, and magnitude of effect associated with these nutritional changes.

In addition to these nutritional challenges, submariners in a DISSUB scenario will potentially experience a host of other DISSUB stressors (e.g., hypoxia, heat stress, and fatigue; Chabal et al., 2019). Co-occurrence of other DISSUB stressors may modulate the effects of nutrition on cognition (D'Agostino et al., 2019; Zhao et al., 2017), and those interactions require further research. Given that field-based research in these areas is not possible, this work must be conducted under DISSUB-relevant laboratory conditions.

While a number of studies have simulated DISSUB-like scenarios in laboratory environments, few have been designed to assess the cognitive performance of survivors. For example, Castellani et al. (2005) studied body fluid regulation during a seven-day simulation, Risberg et al. (2004) examined physiological responses during a six-day simulation (see also Francis et al., 2002), and Berglund et al. (2013) assessed subjects' core body temperature. In perhaps the most realistic simulated DISSUB scenario, researchers at the Naval Submarine Medical Research Laboratory (Horn et al., 2009) sealed two docked submarines and allowed conditions to naturally deteriorate inside the vessels; atmosphere changes and the crews' physical and physiological states were monitored. To the author's knowledge, only one study has examined cognitive performance under simulated DISSUB conditions (Slaven & Windle, 1999); however, that study examined performance under conditions of cold exposure, which is no longer relevant for modern submarines (Berglund et al., 2013; Horn et al., 2009). The need for carefully designed laboratory studies, which closely mirror the conditions expected onboard a DISSUB and assess both the physical *and* cognitive status of crew members, is urgent. Such research should be used to guide countermeasure development to overcome stressors that are within the control of survivors (e.g., supplying caffeine pills in emergency stores in order to prevent the negative effects of caffeine withdrawal on sailors' performance), and to guide policy changes to ensure that uncontrollable stressors (e.g., decreased caloric intake) are as minimally disruptive as possible to crew members' survival efforts.

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