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Stressors Present in a Disabled Submarine Scenario: Part 2. Effects of Environmental, Mental, and Physical Stressors on Cognition

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Survival in a disabled submarine (DISSUB) scenario is predicated upon submariners' abilities to perform demanding tasks that access and use multiple cognitive domains. Survivors must be able to accurately and efficiently react to emergencies, perform stay-time calculations, and make critical decisions while also being exposed to a myriad of stressors that could impair cognitive functioning. Stressors have been identified that could be present in a DISSUB scenario, review of the potential cognitive effects of these stressors, and how these cognitive effects could impair submariner operations during the onboard survival phase of a DISSUB scenario. We discuss the cognitive domains that are likely to affect operational success in a DISSUB scenario, including psychomotor function, attention/vigilance, memory, mathematical processing, cognitive flexibility, risk-taking/impulsivity, and mood. We then conduct a literature review to examine how each DISSUB stressor, identified in the first report of this series, is likely to affect submariner cognition. We highlight knowledge gaps and provide recommendations for future empirical research.

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Abstract

Survival in a disabled submarine (DISSUB) scenario is predicated upon submariners' abilities to perform demanding tasks that access and use multiple cognitive domains. Survivors must be able to accurately and efficiently react to emergencies, perform stay-time calculations, and make critical decisions while also being exposed to a myriad of stressors that could impair cognitive functioning. This report is the second of two that identify the stressors that could be present in a DISSUB scenario, review the potential cognitive effects of these stressors, and consider how these cognitive effects could impair submariner operations during the onboard survival phase of a DISSUB scenario. In the present report, we first discuss the cognitive domains that are likely to affect operational success in a DISSUB scenario, including psychomotor function, attention/vigilance, memory, mathematical processing, cognitive flexibility, risk-taking/impulsivity, and mood. We then conduct a literature review to examine how each DISSUB stressor, identified in Chabal, Bohnenkamper, Reinhart, and Quatroche (2019; the first report of this series), is likely to affect submariner cognition. We highlight knowledge gaps and provide recommendations for future empirical research.

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List of Abbreviations, Acronyms, and Symbols

%	Percent
&	And
<	Less than
>	Greater than
≤	Less than or equal to
≥	Greater than or equal to
°	Degrees
ata	Atmosphere absolute
Cl	Chlorine
CO	Carbon monoxide
CO_2	Carbon dioxide
COHb	Carboxyhaemoglobin
DISSUB	Disabled submarine
e.g.	For example
EABs	Emergency Air Breathing equipment
et al.	And others
ETI	Early Transient Incapacitation
F	Fahrenheit
fsw	Feet sea water
ft	Feet
H_2	Hydrogen
H_2S	Hydrogen sulfide
HCl	Hydrogen chloride
HCN	Hydrogen cyanide
Hz	Hertz
i.e.	In other words
IQ	Intelligence quotient
kcal	Kilocalorie
LiOH	Lithium hydroxide
m	Meters
n.d.	No date
NAVSEA	Naval Sea Systems Command
NH_3	Ammonia
NO_2	Nitrogen dioxide
NSMRL	Naval Medical Submarine Research Laboratory
O_2	Oxygen
OSHA	Occupational Safety and Health Administration
p.	Page
pH	Potential hydrogen
ppm	Parts per million
SEALs	Submarine Escape Action Levels
SEV	Surface equivalent value

SO_2	Sulfur dioxide
SS	Submersible ship (non-nuclear)
U.S.	United States
USS	United States Ship
UVB	Ultraviolet B-ray

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Introduction

A submarine may encounter an event that renders it disabled and unable to surface (Whybourn, Fothergill, Quatroche, & Moss, 2019). Although survivors of this event are instructed to try to remain in place until rescue assets arrive (NAVSEA, 2013b), deteriorating conditions aboard the disabled submarine (DISSUB) may compel submariners to plan for or attempt to execute an escape. Accordingly, submariners' likelihood of survival is dependent on their ability to perform life-sustaining tasks to mitigate present threats, maintain a stable environment, prevent future threats from emerging, and decide when to execute an escape. Unfortunately, however, cognitive processing can be impaired by both internal and external factors (O'Brien et al., 2003; Petersen et al., 1997), and the harsh stressors and conditions expected to be present during a DISSUB scenario (Chabal, Bohnenkamper, Reinhart, & Quatroche, 2019) may impair submariners' abilities to carry out these essential, life-saving operations.

This report is the second in a series of two that identify stressors that may be present in a DISSUB scenario, review the potential cognitive effects of these stressors, and consider how these cognitive effects could impair submariner operations during the onboard survival phase. In the first report of this series (Chabal et al., 2019), we identified potential stressors and categorized them as environmental (e.g., radiation), mental (e.g., confinement/isolation), or physical (e.g., pain/injury). The purpose of this second report is to review how these stressors may lead to deficits in cognitive performance that could affect survival efforts.

In this report, we begin with an overview of the cognitive domains that will likely be required for survival during a DISSUB scenario. We then provide a detailed review of how these domains may be impacted by the stressors expected to be present during a DISSUB event (as outlined in Chabal et al., 2019). For a summary of all findings, we refer the reader to Tables 2-6.

Cognitive Domains Required During a DISSUB Scenario

Psychomotor function. Psychomotor function, which is the intersection of cognition and physical movement, is typically divided into gross motor function (e.g., speed that one can tap one's finger) and fine motor function (e.g., ability to quickly trace a given path; Houx & Jolles, 1993; Karni, 1996). Psychomotor function, both gross and fine, is vital for any tasks requiring dexterity, coordination, or movement (Houx & Jolles, 1993).

During a DISSUB scenario, submariners will be required to have adequate psychomotor function in order to operate and maintain survival equipment. For example, submariners must close compartment doors in the event of a fire or flooding, hang lithium hydroxide (LiOH) curtains to abate the proliferation of carbon dioxide (CO_2), and manually operate valves and other mechanical equipment when performing an escape or when evacuating into rescue submersibles (NAVSEA, 2013b). Decrements to psychomotor function could put submariners at additional risk; for example, submariners with impaired hand strength and coordination could tear the LiOH curtains during installation, resulting in exposure to harmful LiOH dust (Chabal et al., 2019; Horn et al., 2009).

Attention/vigilance. Attention is a relatively simple cognitive process that refers to an individual's ability to selectively concentrate on a particular stimulus or piece of information (Salemink, van den Hout, & Kindt, 2007; Stuss, 2006). Attentional control allows individuals to allocate their limited cognitive resources to a desired purpose (e.g., listening to speech) while inhibiting the processing of extraneous stimuli or information (e.g., background noises; Kayser, Petkov, Lippert, & Logothetis, 2005).

Vigilance is the process of maintaining sustained attention on a desired task for extended periods of time (Warm, Parasuraman, & Matthews, 2008). While vigilance is closely related to attention, vigilance is a more complex process that relies on executive functioning in order to direct and sustain attentional resources (Matthews et al., 2010; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005).

Attention and vigilance are both essential processes in a DISSUB scenario, as submariners are required to continuously monitor their surroundings for risks or dangers and respond quickly and appropriately. A submariner with impaired attention and/or vigilance may fail to observe a change in the surroundings that could present a new risk or danger (e.g., sparks posing a fire hazard), or they may be unable to concentrate on a given task (e.g., reviewing guard book escape procedures).

Memory. Memory is the ability to encode, store, and recall information (Squire, 1987), and is typically divided into short-term memory (i.e., the capacity to hold a small amount of information for a short period of time) and long-term memory (i.e., the retention and recall of factual information and previous experiences; Cowan, 2008). Working memory is often further distinguished from short-term memory and refers to a limited capacity system allowing for the temporary storage and manipulation of information before transfer to short-term memory (Baddeley, Cuccaro, Egstorm, Weltman, & Willis, 1975). Information that is passed from working memory to short-term memory may become encoded in long-term memory through rehearsal of the information (Cowan, 2008).

Submariners in a DISSUB scenario must recall information stored in long-term memory (e.g., training from the Senior Survivor course) and must utilize working memory and short-term memory to encode new information for later recall (e.g., while taking instructions from the DISSUB guard book or from fellow submariners). A submariner experiencing memory deficits may fail to quickly recall information from the DISSUB guard book or trainings, resulting in the improper execution of operations.

Mathematical processing. Mathematical processing refers to the ability to complete numerical calculations and mathematics (Houdé & Tzourio-Mazoyer, 2003; Kaye, 1986). Military operators are frequently required to perform mathematics in the line of duty, such as when performing reconnaissance, organizing logistics, or operating equipment (Chen, 2010).

In a DISSUB scenario, crew members must complete mathematical calculations (e.g., determining the buildup of toxic gases) in order to make critical operational decisions such as when to don emergency air breathers (EABs) or whether to initiate an escape. Incorrect calculations may result in submariners initiating an escape prematurely or failing to take emergency action when degraded conditions jeopardize survival.

Decision making. Decision making is considered a basic cognitive process by which humans select a preferred option of action from among a set alternatives based on certain criteria (Wang, Liu, & Ruhe, 2004). A fundamental part of everyday life, humans make decisions constantly, based on, among other things, experience, expectations, values, emotions, social norms, and risk (Kerstholt & Raaijmakers, 1997). For each decision, whether big or small, individuals assess multiple possibilities and select a final choice or action (Plous, 1993), as a form of problem solving.

Even though many survival decisions in a DISSUB scenario are made using objective criteria (e.g., stay-time calculations), the guard book cannot account for every scenario (NAVSEA, 2013b), and submariners (particularly the senior survivor) must be able to make decisions when situations occur that fall outside the guard book guidelines. For example, survivors could determine that waiting for rescue is the best plan following an initial assessment of the DISSUB; however, the senior survivor might decide to initiate an escape in response to rapidly declining crew morale.

Decision making is a higher-order cognitive task requiring multiple related but distinct processes including cognitive flexibility and risk taking.

Cognitive flexibility. Cognitive flexibility is the ability to selectively switch between different mental processes in response to a changing environment. It allows individuals to switch attention between tasks, and is typically measured using set or task switching behavioral paradigms (Dajani & Uddin, 2015). Sometimes referred to as flexible thinking, cognitive flexibility allows individuals to think about information in different ways and is an important component of decision-making (Brown & Campione, 1981; Dennis & Vander Wal, 2010). Cognitive flexibility allows individuals to selectively engage with or switch to a specific task, and is associated with higher resilience, creativity, and (in older individuals) quality of life (Dajani & Uddin, 2015).

In a DISSUB scenario, there will be many competing demands for attention, such as assessing crew member health, monitoring the atmosphere, recalculating stay-times based on evolving conditions, and attending to onboard emergencies. Switching focus to the variety of tasks that require attention during a DISSUB event requires cognitive flexibility. Deficits in cognitive flexibility could impair the ability of submariners to holistically assess their situation, consider multiple courses of action, and select a plan with the greatest likelihood of survival.

Risk taking/impulsivity. Risk taking refers to an individual's propensity to take a risky action in the hope of a desired result (Galvan, Hare, Voss, Glover, & Casey, 2007; D. C. Glass, 1965; Yates, 1992). A risky action is considered to be one that, on average, results in poorer outcome measures than another action; it often has high reward potential in the short term but ultimately leads to poorer long-term results (Yates, 1992). Risk taking is an essential component of many of the decisions that military operators must make: while a high willingness to accept risk may endanger service members' lives, extreme aversion to risk could result in inaction (Knighton, 2004; Momen et al., 2010).

Risk taking is closely related to impulsivity, which is the tendency to act with limited consideration of consequences, potentially resulting in actions that are poorly conceived or unduly risky (Enticott, Ogloff, & Bradshaw, 2006; Logan, Schachar, & Tannock, 1997). Risk taking and impulsivity vary based on personality and individual factors (Floden, Alexander, Kubu, Katz, & Stuss, 2008; Gianotti et al., 2009; Herman, Critchley, & Duka, 2018; Kreek, Nielsen, Butelman, & LaForge, 2005); however, they also vary situationally (Figner & Weber, 2011; B. Schmidt, Mussel, & Hewig, 2013).

Both risk taking and impulsivity should be minimized in a DISSUB scenario, where it is critical that individuals follow procedures to maximize their likelihood of survival. For example, submariners with increased impulsivity and/or high risk-taking propensity may initiate a dangerous escape even if waiting for rescue is the safest course of action.

Mood. Mood is the subjective emotional state or affect that an individual experiences at any given moment (Larsen & Ketelaar, 1991; Salovey, Rothman, Detweiler, & Steward, 2000). It is composed of multiple orthogonal dimensions (e.g., confused/clearheaded, tense/relaxed, angry/happy, etc.; Booth, Schinka, Brown, Mortimer, & Borenstein, 2006; Shacham, 1983), all of which are critical in supporting military operators' morale (Britt & Dickinson, 2006).

During a DISSUB scenario, negative mood such as substantial sentiments of tension or anger among survivors could lead to interpersonal conflict and a breakdown in the chain of command (Chabal et al., 2019).

Approach

The above-listed cognitive functions (attention/vigilance, memory, mathematical processing, decision making, cognitive flexibility, risk taking/impulsivity, and mood) are expected to be critical for submariners' performance and survival in a DISSUB scenario. A decrement in any one of these functions has the potential for life-threatening consequences. It is well known that individuals' cognitive performance varies intra- and inter-individually based on multiple factors (O'Brien et al., 2003; Petersen et al., 1997); however, to date, there has been little consideration for how the specific stressors present in a DISSUB scenario may impact sailors' cognition (e.g., Francis et al., 2002; House, House, & Oakley, 2000; Slaven & Windle, 1999). In order to fill this gap, we have conducted an in-depth literature review on the effects of the stressors outlined in our previous report (Chabal et al., 2019) on each of the above cognitive domains.

To identify possible studies for this review, we performed literature searches in Google Scholar, Google browser, the Defense Technical Information Center, PubMed, and the archive of Technical Reports from the Naval Submarine Medical Research Laboratory. Searches were conducted with combinations of each individual stressor identified in the previous technical report (Table 1; Chabal et al., 2019) and each of the cognitive domains outlined above (e.g., "heat exposure and mood," "increased pressure and memory," etc.), resulting in 238 search queries (34 stressors × 7 cognitive domains).

Table 1: List of potential DISSUB stressors identified in Chabal et al. (2019)

Environmental Stressors	Mental Stressors	Physical Stressors
Thermal	Confinement/isolation	Pain/injury
Atmospheric composition	Death of shipmates	Nutrition
Air contaminants	Hopelessness	Insufficient water intake
Increased compartment pressure	Boredom	Caffeine withdrawal
Lighting	Conflict among crew members	Fatigue
Flooding		Poor hygiene
Fire		
Noise		
Radiation		

To narrow down the scope of this report, we focus this review on how each of the stressors in Table 1 may affect cognitive performance during or immediately following exposure.

Although long-term, lingering cognitive effects of exposure to DISSUB stressors may arise following the scenario (i.e., in the days, weeks, months, or years following a successful escape or rescue), it is most critical for us to understand submariners' cognition during the onboard survival phase of a DISSUB scenario (i.e., while the boat is disabled and crew members must maximize their chances of survival through escape or rescue).

In the present review we begin with a brief overview of the source of each stressor (for a more detailed discussion of the source, likelihood of occurrence, and range of exposure, see Chabal et al., 2019), and then thoroughly discuss the known cognitive effects of each.

Effects of DISSUB Environmental Stressors

Thermal

There are a number of different thermal changes that can occur during a DISSUB event, including temperature increases or decreases, and increases in humidity. The most likely temperature change is a gradual increase in compartment temperature over the course of days—although it is possible that increases in compartment temperature may occur rapidly in the event of a fire (Berglund, Yokota, & Potter, 2013; Chabal et al., 2019; Horn et al., 2009). Although less likely, the internal compartment temperature could also decrease, for example, if compartments are flooded with cold seawater, the number of survivors is small, and/or chlorate candles are not burned as an oxygen source (Chabal et al., 2019). Regardless of compartment temperature, humidity aboard a DISSUB is expected to increase (Berglund et al., 2013; Chabal et al., 2019).

Increased compartment temperature. Increased compartment temperature can expose individuals to conditions of heat stress that may lead to heat strain. While the definitions for these conditions vary, heat stress is commonly defined as the "environmental and host conditions that tend to increase body temperature" and heat strain is the "physiological and or psychological consequences of heat stress" (Sawka et al., 2003, p. 5); in other words, heat stress refers to the overall heat load to which an individual is exposed, and heat strain refers to the physiological (e.g., heat stroke, heat exhaustion, heat rash) and cognitive consequences of those conditions as the body attempts to dissipate excess heat (Occupational Safety and Health Administration, 2017).

Overall, the physiological effects of heat stress are generally well understood, and injury and illness due to heat exposure have been identified as threats to military populations (e.g., Carter et al., 2005; Epstein, Amit, & Yuval, 2012; Periard, 2017; Rav-acha, Hadad, Epstein, Heled, & Moran, 2004). The effects of heat stress on cognitive processing, however, are less clear (see Hancock & Vasmatzidis, 2003). Due to differences in defining and measuring heat conditions (Hancock & Vasmatzidis, 2003) and to methodological differences across heat-exposure studies (Gaoua, 2010; Taylor, Watkins, Marshall, Dascombe, & Foster, 2016), it can be difficult to determine the temperature threshold at which cognitive performance becomes affected. Differences in the duration of heat exposure, temperature of the environment, humidity, and levels of physical exertion during exposure are all likely to influence results (Backx, Carlisle, & Mcnaughton, 2000; Taylor et al., 2016). Additionally, results can further be affected by differences in participant factors such as demographics (e.g., age, sex, and ethnicity), body composition, previous heat exposure experience, hydration status, and clothing (Burse, 1979; Kenney, 1985; Radakovic et al., 2007; World Health Organization, 1969). Due to these variations, studies exploring the effect of high temperatures on cognitive performance have found mixed results, with some reporting performance decrements in heat (e.g., Hocking, Silberstein, Lau, Stough, & Roberts, 2001) and some reporting no effects (e.g., Haran, Dretsch, & Bleiberg, 2016).

Despite some equivocal results, one consistent finding is that acute heat stress is most likely to affect performance on complex cognitive tasks (Gaoua, 2010; Lee et al., 2014; Taylor et al., 2016), such as those involving working memory (Gaoua, Racinais, Grantham, & El Massioui, 2011) and vigilance (Lenzuni, Capone, Freda, & Del Gaudio, 2014). Interestingly, these decrements are not evident during or immediately following heat stress exposure and may only develop one or more hours after exposure. For example, Morley and colleagues observed no cognitive decrements immediately following 50 minutes of exercise-induced heat stress; however, when participants were tested again 60 and 120 minutes after exposure, performance decrements were observed in both short-term memory and reaction time (Morley et al., 2011). Similarly, Gaoua and colleagues (2011) observed working memory deficits 45 minutes after passive heat exposure but found no deficits in short-term memory or attention within that same time scale. While the precise mechanism behind these decrements is not known, it has been theorized that heat exposure alters the function of brain regions associated with higher-order cognitive function (Liu et al., 2013; Qian et al., 2013). In support of this hypothesis, Lee and colleagues (2014) found that localized cooling to participants' necks following heat stress prevented cognitive decrements on complex cognitive tasks.

One of the cognitive domains that can be negatively impacted by heat exposure is risk taking. Chang and colleagues (2017) found that individuals exposed to heat perceived the same behaviors as less risky and exhibited increased risk-taking behaviors. These findings may help to explain the known link between heat exposure and increased rates of occupational accidents and injuries (Gubernot, Anderson, & Hunting, 2015; Rameezdeen & Elmualim, 2017; Tawatsupa et al., 2013), as workplace incidents may be attributed to increased risk-taking behavior when workers are heat-exposed.

In addition to causing decrements in complex task performance, heat stress is also likely to negatively affect mood and morale. Heat stress is linked to increased aggression (Anderson, 2001), hostility (e.g., Anderson, Deuser, & DeNeve, 1955; Howarth & Hoffman, 1984), depression (Ely, Sollanek, Cheuvront, Lieberman, & Kenefick, 2013), and irritability (NAVSEA, 2013a), as well as decreased vigor (McMorris et al., 2006). Interestingly, these negative effects on mood may emerge even in the absence of task-based performance impairment (e.g., vigilance, grammatical reasoning, etc.; Ely et al., 2013).

While the negative effects of heat stress may be mitigated by acclimatizing individuals to a hot environment (Radakovic et al., 2007), it is unlikely that individuals exposed to heat during a DISSUB will incur this protective benefit. It takes most healthy adults 8 to 14 days to fully acclimatize to heat (Nielsen, Strange, Christensen, Warberg, & Saltin, 1997; Terrados & Maughan, 1995), which is longer than the expected duration of a DISSUB event (NAVSEA, 2013b). It is therefore highly likely that submariners exposed to extreme heat conditions will develop cognitive impairments.

Nevertheless, it is not possible to predict how multi-day, progressive heat stress (as is likely to occur in a DISSUB scenario; Berglund et al., 2013; Chabal et al., 2019) will impact sailors' performance, as the majority of research has focused on the effects of acute heat exposure. Though decrements have been seen to emerge following passive exposure to increasing temperatures over several hours (Wyon, Andersen, & Gunmar, 1979), the effects of passive, progressive heat stress over several days is unknown. This is an important knowledge gap, as the Navy currently does not issue guidance for when increasing heat should require escape from a DISSUB (NAVSEA, 2013b). While some objective, heat-related escape criteria have been developed and proposed, they have not been implemented (Horn, 2009).

Decreased compartment temperature. If survivors in a DISSUB scenario are confined to a flooded compartment or are wearing clothing wet from cold seawater, they may experience a decrease in core body temperature, leading to hypothermia (Chabal et al., 2019; NAVSEA, 2013a). While there are various types of hypothermia (e.g., submersion hypothermia, mountain hypothermia, divers hypothermia; Pozos, Iaizzo, Danzl, & Mills, 1993), survivors during a DISSUB scenario will be most likely to develop immersion hypothermia, which is a condition marked by a decrease in core body temperature upon partial immersion of the body (e.g., hands, legs, lower body) in water as warm as 70°F. Immersion hypothermia develops at a much faster rate than forms of hypothermia caused primarily by air transfer (e.g., mountain hypothermia) because water conducts heat away from the body 25 times faster than air (OSHA).

Hypothermia is likely to impact cognitive functions including psychomotor ability (Fox, 1967; Giesbrecht, Wu, White, Johnstron, & Bristow, 1995; Marrao, Tikuisis, Keefe, Gil, & Giesbrecht, 2005), memory (Coleshaw, Van Someren, Wolff, Davis, & Keatinge, 1983), vigilance (Flouris, Westwood, & Cheung, 2007), decision making (Pomeroy, 2013), and mood (Adam et al., 2008; Francis et al., 2002), though the specific effects depend on the degree of hypothermia experienced (Arthur, 1980). While mild hypothermia may cause skin numbness and slight impairments in psychomotor function, signs of mental confusion and more pronounced muscle incoordination and memory loss are observed as core body temperature continues to drop (NAVSEA, 2013a). “Hypothermic amnesia,” which is characterized by increased mental confusion, reduced consciousness, and impaired memory recall (Jensen & Riccio, 1970; Riccio, Hodges, & Randall, 1968; Richardson, Guanowsky, Ahlers, & Riccio, 1984), is reliably observed in individuals with body temperatures below 95°F (Castellani, Young, Sawka, Backus, & Canete, 1998; Coleshaw et al., 1983; Hoffman, 2002), though mild symptoms may begin to develop even in individuals with core body temperatures above 95°F (Castellani et al., 1998). Interestingly, the most drastic cold-induced impairments of memory occur in the retention and recall of newly-learned information (Coleshaw et al., 1983). This is directly relevant to a DISSUB scenario, as the majority of submariners will not have prior exposure to the DISSUB guard book (Chabal et al., 2019); cold exposure, therefore, may impair submariners’ ability to retain new information critical to their escape/rescue procedures.

It has been hypothesized that cold exposure impacts cognition because it acts as a distractor. This “distraction hypothesis” suggests that cold stress produces a shift in attention from the primary task and causes reduced vigilance and slower reaction time (Teichner, 1958 as cited in Muller et al., 2012). Consistent with this hypothesis, studies have shown that cold exposure affects the pre-frontal cortex of the brain (Correll, Rosenkranz, & Grace, 2005; Porcelli et al., 2008) – which is responsible for cognitive processes including psychomotor function, attention, and memory – through modulation in the levels of central catecholamines that are correlated with cognitive function (Rauch & Lieberman, 1990; Taylor et al., 2016).

Given that cold-exposure is likely to cause deficits in cognition, some research has examined how cognitive functioning recovers following rewarming. In a study by Muller and colleagues (2012), subjects underwent acute cold exposure followed by passive rewarming. Results indicated that cognitive impairments persisted into the recovery period even after passive warming had commenced. Specifically, the study showed that working memory and choice reaction time declined during cold exposure and recovery, and decrements in choice reaction time were still evident 60 minutes after subjects were removed from the cold (Muller et al., 2012). These findings were supported in a neurophysiologic study in which divers exposed to cold water exhibited increased P300 latency (an attention-related brain response) even when core body temperature returned above 95°F (Dutka, Smith, Doubt, Weinberg, & Flynn, 1990). Together, these results suggest that rewarming following cold-exposure will not immediately reverse performance decrements caused by cold exposure during a DISSUB scenario.

Increased humidity. High humidity levels may lead to discomfort, heat strain, dehydration (NAVSEA, 2013a), or thermoregulatory failure (Enander & Hygge, 1990). While high humidity has been linked to multiple health concerns, including an increase in infectious disease and allergic reactions such as asthma (Baughman & Arens, 1996), the effect of humidity on cognitive processing has seldom been investigated. Instead, the majority of research has considered the combined effects of humidity and ambient temperature (e.g., Archibald, 2005; Backx et al., 2000; Melikov, Skwarczynski, Kaczmarczyk, & Zabecky, 2013). Most of the research investigating the effects of humidity on cognitive performance has been conducted in environments such as office spaces and schools (Baughman & Arens, 1996; Singh, Syal, Grady, & Korkmaz, 2010) or during military operations in hot-humid climates (e.g., Caldwell, Engelen, van der Henst, Patterson, & Taylor, 2011). In the latter, the interactions among body armor, physical exertion, and hot-humid conditions on cognitive function complicate the interpretation of results.

Exposure to high humidity has been associated with low activity levels and increased sleepiness (Howarth & Hoffman, 1984; Koots, Realo, & Allik, 2011; Sanders & Brizzolara, 1982). Moreover, several studies have reported that high humidity can negatively affect sleep (e.g., Archibald, 2005; Libert et al., 1988), especially when humidity is combined with high ambient temperature (Archibald, 2005; Okamoto-Mixuno, Tsuzuki, Mizuno, & Iwaki, 2005). In this way, increased humidity may indirectly affect cognitive function by disrupting sleep and leaving survivors susceptible to fatigue (see Fatigue section, p. 37).

Atmospheric Composition

Decreased oxygen levels. During normal operational conditions, the submarine atmosphere is maintained between 18-21% O_2 surface equivalent volume (SEV) in order to optimize physiological and psychological performance (NAVSEA, 2013a). During a DISSUB event, however, the loss of atmospheric control capabilities is likely to result in a progressive decrease in oxygen levels over the course of days (e.g., Chabal et al., 2019; Harvey & Carson, 1989; NAVSEA, 2013a; 2013b), until the mandatory escape limit of 13% O_2 SEV is reached (NAVSEA, 2013b). Once O_2 levels fall below 17-21%, individuals may begin to develop performance deficits associated with hypoxia – a condition in which insufficient oxygen is delivered to body tissues (Cafaro, 1954; NAVSEA, 2013a). Although the physiological effects of hypoxia are generally well understood (e.g., NAVSEA, 2013a; Stricklin & Zeiler, 2011), research exploring the effects of hypoxia on cognition has sometimes produced mixed results.

Although hypoxia has been found to impact cognitive outcomes including reaction time (Fowler, White, Wright, & Ackles, 1982; J. B. Phillips et al., 2009; J. P. Phillips, Drummond, Robinson, & Funke, 2016; A. Smith, 2005), decision making (Nelson, 1982), risk taking (Pighin et al., 2012), visual processing (Fowler, Banner, & Pogue, 1993), working memory (Fowler, Prlic, & Brabant, 1994), and psychomotor function (Nelson, 1982), a number of other studies have failed to demonstrate clear effects (e.g., Balldin et al., 2007; Crow & Kelman, 1971, 1973; Hewett, Curry, Rath, & Stephanie, 2009; Legg et al., 2012; Pilmanis, Balldin, & Fischer, 2016). Similarly, the effects of hypoxia on subjective mood are not clear (Shukitt-Hale & Leiberman, 1996). Although hypoxia has been associated with increased irritability, anxiety, paranoia, depression, and hostility (Ernsting, 1984; NAVSEA, 2013a; Nelson, 1982; Shukitt-Hale, Rauch, & Foutch, 1990; Shukitt & Banderet, 1988; Van Liere & Stickney, 1963), the direction and magnitude of these effects may differ across individuals, with at least one study suggesting that some may experience increased sleepiness and happiness (Shukitt-Hale & Leiberman, 1996).

Many of these conflicting findings are likely attributable to fundamental differences in study design, such as the novelty and sensitivity of the tasks (see discussion in Hewett et al., 2009). For example, negative effects of hypoxia may be mitigated if tasks have been well-learned prior to exposure to hypoxic conditions (Pearson & Neal, 1970). Additionally, the length of exposure to hypoxic conditions is likely to affect results (Balldin et al., 2007; Hewett et al., 2009).

Much of the cognitive research on hypoxia has been conducted in the context of aerospace, where individuals are exposed to oxygen-poor environments with rapid increases in elevation, such as during ascent in a jet plane (e.g., Balldin et al., 2007; Hewett et al., 2009; T. Morgan et al., 2015; J. P. Phillips et al., 2016; Self, Mandella, While, & Burian, 2013). In this context, even mildly-hypoxic conditions lead to decrements in cognitive and operational performance (A. Smith, 2005). However, the type of hypoxia experienced in an aerospace context (i.e., short duration, quick changes in O_2, etc.), is different than the hypoxia that would most likely be experienced in a DISSUB scenario (i.e., progressive depletion of O_2 over the course of days). In a study of simulated DISSUB conditions (Francis et al., 2002), seven-day exposure to 16.75% O_2 SEV did not result in changes to attention, vigilance, working memory, short term memory, or grammatical reasoning.

The longer duration exposure to low oxygen conditions in a DISSUB scenario may actually mitigate some of the negative cognitive effects of hypoxia, as acclimation to lower oxygen levels has been shown to decrease cognitive decrements (Crowley et al., 1992; Pagani, Ravagnan, & Salmso, 1998). Although individuals may experience an initial decline in performance when first exposed to hypoxic conditions, performance gradually returns to baseline as the body begins to adapt (R. F. Chapman, Stray-Gundersen, & Levine, 1998). In a DISSUB scenario, because O_2 levels are likely to decrease gradually over the course of a few days, submariners would experience gradual acclimatization, which could mitigate the effects of hypoxia on cognition. However, it is also unlikely that O_2 levels will plateau in a DISSUB scenario, so complete acclimatization is unlikely. Further research is required to characterize the degree of acclimatization that may occur in individuals exposed to gradually-decreasing O_2 levels over the course of multiple days.

When considering potential effects of hypoxia on cognition in a DISSUB scenario, it is also necessary to consider survivors' level of physical activity. Physical exertion in hypoxic environments may exacerbate the severity of cognitive symptoms or cause symptoms to develop more rapidly due to the increased need for O_2 consumption by the exerted muscle tissue (Hewett et al., 2009). Thus, in a highly-dynamic DISSUB scenario in which submariners are exerting themselves to mitigate casualties (e.g., fighting fires), the crew will likely develop more severe cognitive symptoms and/or will develop them more quickly. Conversely, in a stable DISSUB scenario in which submariners will be able to remain sedentary (NAVSEA, 2013b), the cognitive symptoms of hypoxia may be minimized, delayed, or eliminated.

Increased carbon dioxide levels. During normal operational conditions, the submarine atmosphere is typically maintained at ≤0.5% CO_2 SEV (NAVSEA, 2013a). During a DISSUB event, however, the loss of atmospheric control capabilities is likely to result in a progressive increase in CO_2 levels over the course of days (e.g., Chabal et al., 2019; Harvey & Carson, 1989; NAVSEA, 2013a; 2013b), until the mandatory escape limit of 6.0% CO_2 SEV is reached (NAVSEA, 2013b). Exposure to increased CO_2 levels can lead to hypercapnia – a condition in which CO_2 accumulates in the body, resulting in respiratory acidosis and a drop in blood pH (S. Patel & Majmundar, 2018).

Although the physiological effects of high CO_2 concentrations are well understood (NAVSEA, 2013a), the relationship between CO_2 exposure and cognition is debated (for a review see Stankovic, Alexander, Oman, & Schneiderman, 2016). While some studies have found that elevated CO_2 may impair cognitive functions including decision making (Satish et al., 2012), attention (Schaefer, 1951), mental efficiency (Karlin, 1945), and mathematical processing (Sayers, Smith, Holland, & Keatinge, 1987), these findings are not consistently replicated (Rodeheffer, Chabal, Clarke, & Fothergill, 2018; Ryder et al., 2017; X. Zhang, Wargocki, & Lian, 2016; X. Zhang, Wargocki, Lian, & Thyregod, 2016). In fact, many studies have been unable to establish a relationship between CO_2 exposure and cognitive deficits (e.g., Bloch-Salisbury, 2000; Francis et al., 2002; Sheehy, Kamon, & Kiser, 1982; Vercruyssen, Kamon, & Hancock, 2007).

There have been a few studies that aimed to explore CO_2 exposure specifically within the context of a submarine environment. Observations during World War II submarine patrols on the USS Sailfish (SS-192) led Karlin (1945) to speculate that exposure to CO_2 levels of 3% resulted in impaired mental efficiency (though effects of CO_2 could not be reliably disentangled from other submarine conditions; e.g., hypoxia, lack of sleep, etc.). During Operation Hideout (Faucett & Newman, 1953), sailors were exposed to low levels (1.5% SEV) of CO_2 for 42 days onboard the USS Haddock (SS-231) and failed to exhibit decrements in problem solving ability, complex motor coordination, sensory discrimination, or alertness. Similarly, in a laboratory-based context, the Naval Submarine Medical Research Laboratory did not observe changes to submariners' decision making ability when exposed to the levels of CO_2 (0.06%, 0.25%, and 1.5% SEV) that are expected during normal underway conditions (Rodeheffer et al., 2018).

It is possible that more elevated concentrations of CO_2, as may be expected during a DISSUB scenario (e.g., 2.0% during SURVIVEX 2003; Horn et al., 2009), are necessary to induce cognitive change. In civilian populations, high levels of CO_2 exposure (6.5% and 7.5% SEV) have been associated with difficulties in mathematical problem solving that were not observed at lower exposure levels (0%, 4.5%, 5.5%; Sayers et al., 1987). While it is unlikely that submariners will be exposed to CO_2 levels greater than 6% SEV (NAVSEA, 2013b), these findings may be relevant if escape is not possible (e.g., grounding at deeper than 600 ft, DISSUB crew injured/unfit to escape, unsuitable surface conditions, etc.).

Air Contaminants

Nine air contaminants have been identified as potentially present in the atmosphere during a DISSUB scenario, primarily due to fire (Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988). These gases are: ammonia, carbon monoxide, chlorine, hydrogen chloride, hydrogen cyanide, hydrogen sulfide, lithium hydroxide, nitrogen dioxide, and sulfur dioxide (Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988; Chabal et al., 2019; *Review of Submarine Escape Action Levels for Selected Chemicals*, 2002). The potential cognitive effects of each of these air contaminants are reported individually.

Ammonia. Fires or breach of sanitary tanks in a DISSUB scenario may cause submariners to be exposed to ammonia (NH_3). Regulations indicate that submariners can be exposed to concentrations of 125 parts per million (ppm) for up to 24 hours before they must either escape or don emergency air breathers (EABs; Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988; NAVSEA, 2013a; *Review of Submarine Escape Action Levels for Selected Chemicals*, 2002). At concentrations of 5-50 ppm, NH_3 is detectable by smell (Wands, 1981; World Heath Organization, 1986); at 30-50 ppm individuals begin to experience moderate irritation of the eyes, nose and/or throat (Wands, 1981; World Heath Organization, 1986); at a concentration of 100 ppm, intense irritation to the eyes, nose, and throat is experienced (Ferguson, Koch, Webster, & Gould, 1977). For a more detailed review of NH_3 as an irritant, see the *Review of Submarine Escape Action Levels for Selected Chemicals* (2002).

NH_3 may affect cognition if elevated concentrations remain in the blood for an extended period of time, resulting in low blood oxygen levels (Agency for Toxic Substances and Disease Registry, 2004). However, experimental research on the effects of NH_3 is limited, due to ethical concerns with intentionally exposing research participants to the contaminant. To our knowledge, only one study (Ferguson et al., 1977) has experimentally investigated the effects of acute, industrial NH_3 on occupational performance, though discrete cognitive testing was not performed.

Most studies examining the relationship between chemical exposure and cognition are limited to studying individuals following incidental chemical exposure. For example, Kilburn (2000b) conducted neurobehavioral testing on 12 individuals, 22 months post-accidental exposure to high concentrations of NH_3 following a pipe breaking on an industrial ammonia condenser. Compared to unexposed subjects, the exposed group displayed poorer performance on simple and choice reaction time, color discrimination, visual field tasks, and delayed (but not immediate) verbal recall. While these results suggest that exposure to high levels of NH_3 for a few minutes to several hours may be associated with cognitive impairments, it is not known whether these deficits developed instantly upon exposure or evolved gradually over the 22 months. Moreover, it is impossible to identify the exact exposure levels of the 12 individuals in the experimental group. While these results suggest that NH_3 exposure may have a negative impact on cognition, the effects of DISSUB-like NH_3 exposure (less than 125 ppm exposure for up to 24 hours) on submariner cognition are unknown.

Carbon monoxide. Carbon monoxide (CO) will be produced in a DISSUB scenario from survivor respiration and fire (Brandt-Rauf, Fallon, Tarantini, Idema, & L., 1988; C. J. Clark, Campbell, & Reid, 1981; Hung, Lin, Wang, & Chan, 2006), resulting in submariners potentially be exposed to CO concentrations of 150 ppm for up to 24 hours before they must either escape or don EABs (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002). When individuals are exposed to CO from the atmosphere, it binds to their hemoglobin and forms carboxyhaemoglobin (COHb) in the blood (*Acute Exposure Guideline Levels for Selected Airborne Chemicals*, 2010). Elevated levels of COHb impede oxygen delivery and can result in localized hypoxia (*Acute Exposure Guideline Levels for Selected Airborne Chemicals*, 2010).

Common physiological symptoms of carbon monoxide (CO) exposure include headaches, dizziness, weakness, upset stomach, vomiting, chest pains, and unconsciousness; however, individuals may experience lethal concentrations of CO while sleeping before showing any symptoms (Center for Disease Control and Prevention, 2018). Although CO exposure has been well studied, the threshold concentrations that provoke specific symptoms have yet to be quantified. In general, COHb levels greater than 20% are likely to be toxic, and levels higher than 50% are lethal (Segan's Medical Dictionary, 2012).

Studies on the cognitive effects of CO exposure report mixed results. While several studies have shown degraded performance on vigilance tasks following moderate CO exposure (50-100 ppm; 2.3 % COHb; Beard & Grandstaff, 1975; Bender, Goethert, & Malorny, 1972; Bunnell & Horvath, 1989; Davies, Jolly, Pethybridge, & Colquhoun, 1981; Davies & Smith, 1980; Fodor & Winneke, 1972; Horvath, Dahms, & O'Hanlon, 1971), other studies have found no effects on vigilance, memory, or mathematical processing even at CO concentrations up to 250 ppm (7.5% COHb; Beard & Grandstaff, 1975; Benignus, Muller, Barton, & Prah, 1987; Benignus, Otto, Prah, & Benignus, 1977; Ekblom & Huot, 1972; Ettema et al., 1975; Ramsey, 1973; Stewart et al., 1970). To our knowledge there has not been any research that has examined the cognitive effects of CO exposure at levels that would be expected in a DISSUB event (less than 150 ppm for up to 24 hours).

Chlorine. Chlorine (Cl) will be produced in a DISSUB scenario from the burning of chlorate candles and if seawater comes in contact with battery terminals, (NAVSEA, 2013a, 2013b) resulting in submariners potentially being exposed to Cl concentrations of 2.5 ppm for up to 24 hours before they must either escape or don EABs (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002).

Acute exposure to high concentrations of Cl following industrial accidents has been found to produce long-term deficits in memory, attention, vocabulary, psychomotor function, and problem solving, as well as visual, vestibular, and auditory sensory deficits (Auerbach & Hodnett, 1990; Kilburn, 2000a, 2003a, 2003b). Furthermore, these cognitive and sensory deficits increased over a period ranging from 3 to 4.5 years (Kilburn, 2000a, 2003a, 2003b). However, as is the case with accidental exposure studies, it is not possible to determine the exposure concentration or the time course of cognitive deficits during and immediately following the exposure (Agency for Toxic Substances and Disease Registry, 2010; Kilburn, 2000a, 2003a, 2003b). It is likely that these exposure concentrations exceed what a submariner would experience in a DISSUB scenario, and it is possible that DISSUB-like exposure to Cl (less than 2.5 ppm for up to 24 hours) would be insufficient to affect cognition. Further research is required to validate this assertion.

Hydrogen chloride. Fires in a DISSUB scenario will produce hydrogen chloride (HCl; Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988; R. F. Dyer & Esch, 1976), and submariners may experience HCl concentrations of 35 ppm for up to 24 hours before they must either escape or don EABs (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002).

HCl primarily targets the eyes, skin, and respiratory system and does not directly target the central nervous system; therefore, it is unlikely to alter cognition (Center for Disease Control and Prevention, 2016). However, HCl may affect cognitive performance due to secondary symptoms. For example, HCl forms hydrochloric acid when combined with water in the body, becoming highly corrosive to any tissue it contacts (Agency for Toxic Substances and Disease Registry, 2002). Pain resulting from this reaction may result in an inability to maintain focus on tasks (see Pain/Injury section, p. 28; Eccleston & Crombez, 1999). Overall, however, there is insufficient evidence to suggest that DISSUB-like exposure to HCl (less than 35 ppm for up to 24 hours) would affect submariner cognition.

Hydrogen cyanide. Fires in a DISSUB scenario will produce hydrogen cyanide (HCN; Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988; C. J. Clark et al., 1981), and safety protocols indicate submariners may be exposed to HCN concentrations of 15 ppm for up to 24 hours before they must either escape or don EABs (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002).

HCN exposure interferes with the normal use of oxygen in nearly every organ of the body, and it primarily affects the central nervous system, cardiovascular system, and pulmonary system (Center for Disease Control and Prevention, 2011). Experimental data suggest that acute exposure to high levels of HCN (500 - 625 ppm) can cause changes in mood, including increased giddiness, confusion, restlessness, and anxiety (Barcroft, 1931; Center for Disease Control and Prevention, 2011). However, these concentrations exceed what submariners would likely experience in a DISSUB scenario (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002). To our knowledge, no studies have examined the effects of HCN on objective cognitive functioning or at concentrations likely to be experienced in a DISSUB scenario.

Hydrogen sulfide. Individuals in a DISSUB scenario may be exposed to hydrogen sulfide (H_2S) from sewage (Chabal et al., 2019; L. Zhang et al., 2008); however, there are no defined thresholds for what H_2S concentrations require submariners to take actions to avoid exposure (i.e., initiating escape or donning EABs; *Review of Submarine Escape Action Levels for Selected Chemicals*, 2002).

To our knowledge, the only experimental study investigating the cognitive effects of hydrogen sulfide found that acute exposure to low concentrations of H_2S (0.05-5 ppm) decreased verbal learning ability (Fiedler et al., 2008). As these conditions are representative of what submariners may experience in a DISSUB scenario, H_2S may be expected to affect cognition in a DISSUB scenario; however, further research is required to replicate and expand upon these results.

Lithium hydroxide. Through contact with materials designed to eliminate the build-up of CO_2, sailors in a DISSUB scenario may be exposed to low concentrations of LiOH (Chabal et al., 2019; Horn et al., 2009). It is likely that exposure times will be brief, as LiOH rapidly dissolves in the atmosphere (Horn et al., 2009).

LiOH is considered hazardous when dust comes into contact with skin or eyes, or when it is ingested or inhaled (PubChem, 2005). Skin contact can produce inflammation, itching, scaling, reddening, or severe blistering (PubChem, 2005; ScienceLab.com, 2005). When inhaled or ingested, LiOH dust can cause chemical burns to the respiratory tract, along with coughing and wheezing that may lead to gastrointestinal tract burns, abdominal pain, nausea, vomiting, diarrhea, and corrosion of the esophagus (ScienceLab.com, 2005). Although the Material Safety Data Sheet (ScienceLab.com, 2005) for LiOH indicates that ingestion of LiOH may affect the central nervous system by inducing headaches, tremors, disorientation, confusion, irritability, and impaired concentration, we have found no record of controlled human subjects studies that document these cognitive effects. Further research on the potential cognitive effects of LiOH exposure is required.

Nitrogen dioxide. Nitrogen dioxide (NO_2) will be produced in a DISSUB scenario in the event of fires (Bolstad-Johnson et al., 2000; Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988; Radke, Stith, Hegg, & Hobbs, 1978). Due to the respiratory complications associated with breathing air that contains increased NO_2 concentrations (e.g., Australian Government Department of the Environment and Energy, 2005; United States Environmental Protection Agency, 2018), submariners can be exposed to NO_2 concentrations of 1 ppm for up to 24 hours before they must either initiate escape or don EABs (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002).

The cognitive effects of NO_2 exposure have primarily been investigated alongside co-pollutants, such as CO (e.g., Chang et al., 2014) or general traffic-related emissions. For example, urban-dwelling adults exposed to ambient NO_2 levels greater than 0.02 ppm demonstrated decrements to memory recall (Gatto et al., 2014). Similarly, exposure to traffic-related air pollution is associated with decreased cognitive function in older men (71 ± 7 years of age; Power et al., 2011). However, as these studies did not isolate the effects of NO_2 on cognition, it is unknown whether the observed cognitive decrements are attributable to NO_2 or to other pollutants (e.g., ozone, particulate matter, etc.) present in the air. Moreover, chronic NO_2 exposure over months to years (as experienced as a result of traffic-related emissions) is not representative of what submariners may experience in a DISSUB scenario (Chabal et al., 2019).

Sulfur dioxide. Sulfur dioxide (SO_2) will be produced in a DISSUB scenario in the event of fires (Bolstad-Johnson et al., 2000; Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988). Protocol dictates that submariners can be exposed to SO_2 concentrations of 6 ppm for up to 24 hours before they must either escape or don EABs (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002).

Exposure to SO_2, in combination with other air contaminants (nitric oxide, NO_2, CO, and methane hydrocarbon), has been associated with increased stress and decreased mental concentration and mood (Bullinger, 1989). However, it is not possible to disentangle the effects of SO_2 from the effects caused by other contaminants; to our knowledge, no research has evaluated the independent effects of SO_2 exposure on cognition.

Increased Compartment Pressure

Pressure aboard a DISSUB will increase due to any flooding or due to survivors' use of EABs (Chabal et al., 2019; NAVSEA, 2013b). Any rise in compartment pressure causes the solubility of gas in the body's tissue to increase (Whitaker & Findley, 1977). Not only does this exacerbate the effects of previously-reviewed carbon dioxide (see Increased Carbon Dioxide subsection, p. 10) and air contaminants (see Air Contaminants section, p. 10), it also introduces two novel stressors: increased oxygen partial pressure and increased nitrogen partial pressure (Chabal et al., 2019).

Increased oxygen partial pressure. Breathing oxygen at increased pressure (i.e., partial pressure) can lead to oxygen toxicity– a condition in which the body tissue absorbs an excess amount of oxygen (NAVSEA, 2011 [Change A]; Vann, 1988). Symptoms of oxygen toxicity primarily manifest in the central nervous system (when individuals are exposed to very high oxygen partial pressures for short amounts of time) and the pulmonary and ocular systems (when exposed to less elevated partial pressures for longer periods). Symptoms can include respiratory irritation and, at incredibly high pressure, blurred vision, ear pain, nausea or sporadic vomiting, twitching and tingling, irritability, dizziness, and convulsions (Whybourn et al., 2019). These symptoms typically begin after 36-48 hours of continuous exposure but may be seen as early as 24 hours after exposure. The only treatment for oxygen toxicity is to decrease pressure or to shift the gas composition — the first is not possible in a DISSUB scenario and the second can only be achieved by survivors gradually breathing down the oxygen content (NAVSEA, 2011 [Change A]).

Multiple reports have investigated the biochemical mechanisms of oxygen toxicity (e.g., Baeyens & Bonnett, 1947; Cadenas, 1989; Halliwell & Gutteridge, 1984) and indicate that oxygen itself is not toxic; rather, toxic by-products are produced as a result of cellular respiration (Vann, 1988). However, while the physiology of this process is relatively well understood (J. M. Clark, 1993; J. M. Clark & Lambertson, 1971; NAVSEA, 2011 [Change A], 2013a), the cognitive effects of oxygen toxicity are less known.

Early studies from the 1960s and 70s suggested that increasing oxygen partial pressures could potentiate nitrogen narcosis, and that raised oxygen partial pressures alone could result in narcosis (P. B. Bennett, 1993; Frankenhaeuser, Graff-Lonnevig, & Hesser, 1963). More recently, a 2016 study assessed the interaction of hyperbaric N_2, CO_2, and O_2 on cognitive function, and reported that at hyperbaric pressures, O_2 exposure was associated with motor function, attention, and memory impairment (when the inspired partial pressure of nitrogen was 4.5 ata or greater; Freiberger et al., 2016). However, another study that assessed the effects of increased O_2 and CO_2 partial pressures on working memory did not detect any changes in scores when O_2 pressure increased from 0.21 ata to 1.30 ata, and in fact reported that increased O_2 partial pressure may counteract degradations in performance due to elevated CO_2 partial pressure (Gill et al., 2014). Additionally, in a Naval Submarine Medical Research Laboratory (NSMRL) study (Kinney, Luria, Strauss, McKay, & Paulson, 1974), participants lived in a hyperbaric chamber (60 fsw) for one month at mild oxygen partial pressure. No effects on visual acuity were observed, though no other cognitive domains were assessed. It is likely that the oxygen partial pressure experienced in a DISSUB scenario would be greater than that experienced in this experiment (Chabal et al., 2019).

Thus, while results are mixed, there is evidence that increased oxygen partial pressures would lead to cognitive impairments. Researchers reported that observed cognitive impairments were rapidly reversed when pressures and concentrations returned to normal, and, to date, have been unable to determine if cognitive impairments are due to O_2 narcosis or O_2 toxicity (Freiberger et al., 2016; Gill et al., 2014). Additional research on cognitive effects of increased oxygen partial pressures likely during a DISSUB event is warranted.

Increased nitrogen partial pressure. Breathing nitrogen at high partial pressure can result in a reversible condition known as nitrogen narcosis (Whitaker & Findley, 1977). The symptoms of nitrogen narcosis, which are reliably detected at a pressure of 4 ata and are drastically noticeable at 8 ata (NAVSEA, 2011 [Change A]), are widely compared to the effects of alcohol intoxication, including alterations to mood and behavior (e.g., Hobbs, 2008; Monteiro, Hernandez, Figlie, Takahashi, & Korukian, 1995; Unsworth, 1966). Cognitive deficits associated with nitrogen narcosis include mathematical errors (Behnke, Thomson, & Motley, 1935), memory impairment (Hobbs, Higham, & Kneller, 2014; Hobbs & Kneller, 2009; Kneller &

Hobbs, 2013; Tetzlaff et al., 1998), loss of psychomotor coordination (Behnke et al., 1935), slowing of mental activity (Poulton, Catton, & Carpenter, 1964), impaired vigilance (Petri, (2003; Whitaker & Findley, 1977), and a reduction in pain perception (Kowalski et al., 2012) (see J. E. Clark, 2015 for a further review on the psychological effects of nitrogen narcosis). Performance decrements are likely to be greater for complex tasks (Whitaker & Findley, 1977).

Unlike many other stressors present in a DISSUB scenario, nitrogen narcosis may induce positive changes in mood, such as increases in excitement and feelings of euphoria (Behnke et al., 1935; NAVSEA, 2011 [Change A]; Petri, 2003). Behnke and colleagues (1935) described individuals who were exposed to pressures greater than 4 ata occasionally expressing spontaneous “laughter and loquacity” (p. 555). This improved mood can instill false feelings of well-being in individuals and jeopardize their ability to act effectively in emergency situations (NAVSEA, 2011 [Change A]). For example, divers experiencing narcosis have been seen to swim at dangerous depths without concern for their air supply (J. E. Clark, 2015; NAVSEA, 2011 [Change A]). Conversely, nitrogen narcosis has also been reported to negatively impact mood states, inducing a state of anxiety and impairing reasoning ability (Hobbs, 2008).

The effects of nitrogen narcosis may be a function of the time spent under conditions of increased pressure (T. C. Schmidt, Hamilton, Moeller, & Chattin, 1974). Some evidence suggests the effects of nitrogen narcosis are more evident in those who have prolonged exposure to nitrogen partial pressure than those who are only exposed for a short duration (T. C. Schmidt et al., 1974). Although individuals may develop a tolerance to the effects of narcosis through repeated exposure to partial pressure, it is unlikely that submariners would have a tolerance (i.e. the DISSUB event would likely be their first experience being under increased pressure). Fortunately, the pressure at which nitrogen narcosis reliably develops (greater than 4 ata) is near the maximum pressure reached in a survivable DISSUB scenario (Whybourn et al., 2019); therefore, nitrogen narcosis is likely to have minimal effect on survival efforts for most shallow, pressurized DISSUB situations.

Lighting

In most DISSUB scenarios, normal power stores will be unavailable and submariners must operate using emergency lighting. Not only is some of this emergency lighting fitted with red filters (A. Quatroche, personnel communication, October 16, 2018), but it is also dimmer and provides less illumination than would be experienced under normal operations (Chabal et al., 2019; NAVSEA, 2013b).

As is outlined below, most research on the effects of light exposure has focused on relatively short-duration changes. In a DISSUB scenario, survivors will experience adverse lighting conditions continuously for up to seven days (Chabal et al., 2019); thus, cumulative effects may develop and become evident over time. Additional research is required in order to fully understand the impact of a DISSUB-like lighting environment on submariners’ cognitive abilities.

Dim lighting. In the event of a loss of power, the presence and usability of alternative lighting sources are key factors in determining the likelihood of survival during a DISSUB scenario (NAVSEA, 2013b). Sufficient lighting is required for many cognitively-demanding tasks such as reading the guard book, completing stay-time calculations, assessing and correcting damage to the boat, navigating the internal environment, assisting in the care of injured crew members, and initiating and conducting escape. Therefore, the largest lighting-related risk to submariners' performance is impaired vision that limits sailors' ability to carry out survival tasks.

A dim lighting environment may also lead to negative impacts on submariners' mood. In animal studies, prolonged exposure (six weeks) to darkness has been associated with depressive behaviors (Ashkenazy-Frolinger, Kronfeld-Schor, Juetten, & Einat, 2010) and psychomotor dysfunction (Gonzalez & Aston-Jones, 2007). Although a DISSUB scenario is not expected to last six weeks, humans' increased sensitivity to darkness may lead to the rapid development of these effects (Gonzalez & Aston-Jones, 2007). Depressive mood states during a DISSUB event are likely to induce cognitive impairments in judgement (Botle, Goschke, & Kuhl, 2003), memory and learning (Fonken, Kitsmiller, Smale, & Nelson, 2012), and information processing (S. M. Smith & Petty, 1995).

In contrast to these negative effects, however, there is some evidence that short-term light deprivation may actually lead to improvement of performance in non-visual domains. For example, after only 90 minutes of dark exposure, participants perform significantly better on tasks of tactile spatial acuity (Facchini & Aglioti, 2003), sound localization (Lewald, 2007), and the perception of complex sounds (Landry, Shiller, & Champoux, 2013). While the effects are reversible (i.e., performance returns to baseline once light is re-introduced), these findings suggest that some tasks during a DISSUB event (e.g., listening for rescue assets) may benefit from a dim lighting environment.

Red lighting. The use of red light aboard submarines has long been criticized for having deleterious effects on operational performance (Kinney, Neri, Mercado, & Ryan, 1983; Luria & Kobus, 1985; Luria, Socks, & Kobus, 1986). When compared to low-level white light, red lighting is more likely to cause eye strain in crew members standing watch, as it interferes with submariners' ability to read color-coded charts or printed materials (Luria & Kobus, 1985). Moreover, exposure to red light has been linked to increased feelings of anger, hostility, anxiety, and depression (Han & Lee, 2017). Nevertheless, only a small percentage of submariners report difficulty operating during red light exposure (Kinney et al., 1983).

Flooding

In the event of flooding in a DISSUB scenario, an unexpected influx of water may result in exposure to cold conditions and/or in increased compartment pressure (see Decreased Compartment Temperature, p. 7 and Increased Compartment Pressure, p. 14). Moreover, submariners may become submerged (i.e., total body under water) or immersed (i.e., part of body under water) in seawater (Chabal et al., 2019).

Several studies have reported declines in psychomotor function (e.g., finger tapping) when submerged, with worsening performance observed at increasing submersion depths (e.g., Hancock & Milner, 1982; Mears & Clearly, 1980). Deficits have also been observed to higher-order executive processing when divers were submerged at depths of five meters (Dalecki, Bock, & Schulze, 2012) or twenty meters (Stanley & Scott, 1995; Steinberg & Doppelmayr, 2017). These findings are likely not directly relevant for performance during a DISSUB scenario, however, as survivors are unlikely to become submerged at the depths tested in these studies and are more likely to experience partial water immersion (Chabal et al., 2019).

Seo, Kim, Edward, Glickman, & Muller (2013) studied immersion conditions that would be more akin to those experienced during a DISSUB event. When immersed in either thermo-neutral (35°C) or cold (13°C) water up to the iliac crest (hip bone), volunteers did not display any changes in mood or selective attention. However, following removal from the cold (but not the neutral) water, selective attention decreased (Giesbrecht, Arnett, Vela, & Bristow, 1993). It is likely that this performance decrement is attributed to recovery from cold and to the distracting effects of cold skin temperature (Cheung, Westwood, & Knox, 2007), rather than to immersion itself. Therefore, it is expected that the largest threat to submariners' cognition in the event of flooding is exposure to cold water and hypothermic conditions.

Fire

Fires may occur as the inciting event of a DISSUB scenario or as a result of factors such as electric short circuiting (Chabal et al., 2019; Hoover, Bailey, Willauer, & Williams, 2005). When a fire occurs during a DISSUB event, crew members must act immediately to stabilize casualties and maximize crew survival time (NAVSEA, 2013a). Even for crew members not actively involved in the firefighting efforts, the residual effects of a fire event (e.g., a build-up of heat, smoke, and toxic chemicals) are felt by all survivors.

The majority of research on the effects of fire on human performance has focused on firefighter fatalities, crowd behavior during fires (e.g., Hodous, Pizatella, Braddee, & Castillo, 2004; Kuligowski, 2009), the leadership skills of firefighters (e.g., Useem, Cook, & Sutton, 2005), adverse health effects associated with fires (e.g., Sheridan, 2016), and decision making during fire simulations (e.g., Cole, Vaught, Wiehagen, Haley, & Brnich, 1998). While inhalation injury has been identified as the most likely threat to survivability during a fire event (Gann, Babrauskas, & Peacock, 1994; Sheridan, 2016; Stefanidou, Athanaselis, & Spiliopoulou, 2008), the overall health effects of fire exposure are still poorly understood. This is because most of the knowledge surrounding the health effects on humans has been gathered through case reports (e.g., Alarie, 2002), where there is large variety between the cases, the diagnostic criteria are unclear, and the risk of deaths is difficult to quantify (Hodous et al., 2004). Some animal research has attempted to demonstrate the health effects of smoke inhalation and burns (e.g., Nieman, Clark, Wax, & Webb, 1980; Zawacki, Jung, Joyce, & Rincon, 1977), but little research has explored the independent cognitive dysfunctions that may occur due to the presence of fire.

In a study of decision-making while firefighting, subjects reported making decisions within 30-60 seconds of an event and rarely reported weighing alternative options, suggesting that decisions were made based on skill or past experience rather than on reasoning (Klein, Calderwood, & Clinton-Cirocco, 1988). However, this finding is likely dependent upon the amount of experience that responders have in a fire environment (Kuligowski, 2009). Therefore, depending on submariners' training and experience with fire scenarios, their decision making processes may be affected differently. There has been no research, to our knowledge, exploring the impact of a fire event on other cognitive processes.

Noise

In a DISSUB scenario individuals will experience low ambient noise levels due to lack of running machinery (Chabal et al., 2019). It is likely that the only source of DISSUB-specific environmental noise will come from intermittent hull tapping that may be used to communicate with on-scene rescue crews (NAVSEA, 2013b). Though this intermittent noise may serve as a cognitive distraction, resulting in the diversion of attention (Arnsten & Goldman-Rakic, 1998), it is more likely that any potential cognitive impacts stem from the *absence* of noise in a DISSUB scenario. Unfortunately, however, current research is unable to conclusively suggest whether an absence of noise would impart a cognitive benefit or decrement.

Many studies have suggested that the presence of background noise negatively affects cognitive functioning in both humans (e.g., Basner et al., 2014; Cassidy & MacDonalds, 2007; Danbury & Berry, 1998; Mehta & Cheema, 2013; Söderlund, Sikstrom, Loftesnes, & Sonuga-Barke, 2010; Söderlund, Sikstrom, & Smart, 2007) and animals (Arnsten & Goldman-Rakic, 1998; Cheng, Wang, Chen, & Liao, 2011). For example, noise exposure has been correlated with reading deficits and may interfere with speech perception and long-term memory (Hygge, Evans, & Bullinger, 2002). One proposed mechanism for this effect is that processing ambient background noise draws cognitive resources away from other tasks (Cassidy & MacDonalds, 2007; Sarampalis, Kalluri, Edwards, & Hafter, 2009). This would suggest that an *absence* of background noise, therefore, might facilitate cognitive processing (though, to our knowledge, this has never been explicitly studied).

Conversely, some studies have suggested that moderate levels of background noise can improve cognitive functioning. Mehta and Cheema (2013) observed that individuals had enhanced abstract cognitive processing when exposed to moderate levels of background noise compared to low and high levels of background noise. This may be because the presence of moderate levels of background noise increases arousal and counteracts feelings of boredom (Söderlund et al., 2010). Thus, the absence of noise in a DISSUB scenario may lead to decreased cognitive functioning due to low arousal and intense feelings of boredom.

Whether an absence of background noise has an impact on cognitive function may depend on factors including whether crew members are sleep deprived (Tassi et al., 1993), the time of day at which the distracting noise occurs (Tassi et al., 1993), the surrounding lighting environment (Hygge & Knez, 2001), or environmental temperature (Hygge & Knez, 2001). For example, Tassi and colleagues (1993) found that the presence of noise at 0500 reduced response time and helped overcome decrements to performance while individuals were in their circadian trough; noise at 0800, however, led to decrements in performance. Other research has suggested an interaction between noise and air temperature, with noise negatively impacting long-term memory recall at 80°F but not at lower temperatures (Hygge & Knez, 2001). The interaction of noise and temperature is likely to be particularly relevant for a DISSUB scenario, as temperature is expected to increase over the duration of the event (Chabal et al., 2019; Horn et al., 2009; NAVSEA, 2013b).

Radiation

Although radioactive leaks or contamination have not occurred in any historical DISSUB events (Whybourn et al., 2019), sufficient damage to the nuclear reactor may result in submariners being exposed to ionizing radiation (Chabal et al., 2019; Mueller, Weishar, Hallworth, & Bonamer, 2018).

Ionizing radiation exposure affects almost every major organ system in the human body due to the deposition of energy (D'Anci, Mahoney, Vibhakar, Kanter, & Taylor, 2009). This then results in reactive chemical products (free radicals) that can combine with the body's chemicals to form reactive elements, resulting in further cellular damage (Carpenter, 1979; D'Anci et al., 2009). There are a variety of factors that may affect the degree of cellular damage, such as the radiation's quality, dose, dose rate, and cell sensitivity (Lenard, Forcino, & Walker, 2012). High doses can lead to death within hours or days (Carpenter, 1979). For a further review of the physiological effects of radiation, see Briggs (1962) and the Naval Nuclear Propulsion Program's Occupational Radiation Exposure from U.S. Naval Nuclear Plants and Their Support Facilities (Mueller et al., 2018).

Much of what is known about the relationship between radiation exposure and cognitive functioning pertains to long-term effects following acute exposure. Only after the Chernobyl incident in 1986 did the scientific community begin to study the effects of accidental exposure to ionizing radiation on cognitive functioning (see Bromet, Havenaar, & Guey, 2011 for a detailed review). The majority of research has focused on three specific groups: children that were exposed to radiation in utero or as infants (e.g., Bromet et al., 2011; Hall et al., 2004; Joseph, Reisfeld, Tirosh, Silman, & Rennert, 2004; Loganovsky, 2009; Schull & Otake, 1999), the clean-up workers responsible for site-remediation after nuclear accidents (e.g., Bromet et al., 2011; Gamache, Levinson, Reeves, Bidyuk, & Brantley, 2005), and human populations who lived in close proximity to the immediate area of the accident (e.g., Bromet et al., 2011; Gamache et al., 2005; Joseph et al., 2004). These studies have found that children and adults exposed to radiation exhibit long-term symptoms including a loss of mental power, reduced efficiency, and psychomotor slowing (Gamache et al., 2005; Hall et al., 2004). Those who received the greatest radiation exposure (i.e., clean-up workers) experienced significantly higher rates of depression, suicidal ideation, and post-traumatic stress disorders (Bromet et al., 2011). Further surveys have found that exposed adults experienced a higher rate of psychological distress, sleep disturbances, fatigue upon wakening, and general concern (Ginzburg, 1993). Delayed effects of ionizing radiation exposure may include cancer, lower mean IQ, speech and language disorders, emotional disorders, an increased rate of aging, and severe intellectual impairment (Bromet et al., 2011; Kimler, 1998; Kolominsky, 1999; Lenard et al., 2012; Mendola, Selevan, Gutter, & Rice, 2002; Otake & Schull, 1998; Schull & Otake, 1999; Yamazaki & Schull, 1990).

In addition to reports detailing accidental radiation exposures, the effects of radiation have also been seen through clinical experiments examining the effects of radiation therapy (e.g., Butler, Rapp, & Shaw, 2006; Douw et al., 2009; Duffner, 2004); however, the majority of this research is directed towards whole-brain irradiation, rather than whole-body irradiation as would occur during a DISSUB. Nonetheless, cognitive decrements such as progressive impairments in memory, attention, and executive function increase when individuals are exposed to ionizing radiation (Greene-Schloesser & Robbins, 2012; Mizumatsu et al., 2003). These cognitive deficits are believed to be the result of reductions in the hippocampal neurogenesis and changes to other regions of the brain (Greene-Schloesser & Robbins, 2012; Mizumatsu et al., 2003).

There are challenges with interpreting reports of nuclear accidents and therapy-based exposures that limit the ability to draw conclusions regarding the potential effects of radiation on cognitive functioning in a DISSUB scenario. First, although there is evidence to suggest that ionizing radiation exposure affects human cognitive performance, it is difficult to quantify the effects due to the limited available data; most studies are only able to assess individuals after accidental exposure, and baseline data are absent (Loganovsky, 2009). Therefore, the true extent of psychological and cognitive effects from radiation exposure is unknown, as some individuals may have had pre-existing conditions that mediated the effects of radiation exposure. Moreover, many of the effects reported in the literature may have developed over time, and there is no way to determine if the performance decrements were present within a few minutes or hours after exposure or whether they developed years after exposure. Finally, due to the correlational nature of observational research, it is impossible to link observed effects directly to radiation exposure. For example, impacts of radiation exposure may either be attributed to direct effects of radiation on the central nervous system or to indirect effects of illness from radiation (Gamache et al., 2005).

Environmental Stressors Conclusions

The key findings for each environmental stressor are summarized in Table 2, as well as knowledge gaps in how these findings may generalize to a DISSUB scenario. Areas of future research are outlined where appropriate. Overall, there is evidence to suggest that a number of environmental stressors will affect cognition, including thermal changes (increased and decreased compartment temperature), atmospheric gas composition (decreased oxygen levels and increased carbon dioxide levels), and increased oxygen and nitrogen partial pressures. Others, such as fire or hydrogen chloride are unlikely to directly impact cognition. A lack of experimental data precludes us from drawing conclusions about the impact the remaining environmental stressors would have on cognitive functioning during a DISSUB scenario.

Table 2: Summary of key findings and knowledge gap(s) for environmental stressors.

Stressor	Summary of Key Findings	Knowledge Gap(s)
Thermal		
Increased compartment temperature	Increased compartment temperature is most likely to affect performance on complex cognitive tasks, such as those involving working memory; risk taking and mood are also likely to be impacted by heat stress. There may be a delay between heat exposure and deficit manifestation. Deficits may be abated by localized cooling to the neck.	The majority of past research has focused on the cognitive effects of acute heat stress. The effect of exposure to progressively increasing temperature over several days is largely unknown.
Decreased compartment temperature	Decreases in core body temperature can impair psychomotor function, memory, decision making, and mood. Cognitive deficits may persist following rewarming.	While there is evidence for the effects of cold-exposure on higher-order cognitive processes, those findings should be further replicated by future work.
Increased humidity	Increased humidity may indirectly affect cognition by disrupting sleep, resulting in fatigue-related decrements.	The majority of research has investigated the overall effects of humidity and temperature together, thus the independent effects of humidity on cognition are largely unknown.
Atmospheric Gas Composition		
Decreased oxygen (O_2) levels	Hypoxia may lead to impaired decision making, reaction time, visual processing, working memory, and psychomotor function, though some studies have failed to detect cognitive impairment due to low O_2 levels. Cognitive effects may be mitigated through acclimatization to oxygen-poor environments.	The majority of hypoxia research has been conducted in an aerospace context (rapid, short-term changes in O_2); future research should consider effects of exposure to progressive depletion of O_2 over the course of days.

Stressor	Summary of Key Findings	Knowledge Gap(s)
Increased carbon dioxide (CO_2) levels	Results are mixed; some studies report decrements in decision making and mathematical processing while others report no impairment in cognitive function.	Additional research is required to understand the effects of exposure to progressive accumulation of CO_2 over the course of days.
Air Contaminants		
Ammonia (NH_3)	Research is limited to studying individuals who were accidentally exposed; exposure to high levels of NH_3 may be associated with cognitive impairments.	The exact level of exposure that results in cognitive deficits and the time course for developing deficits under DISSUB-like exposure are unknown. Ethical considerations will limit the future study of NH_3 on cognition.
Carbon monoxide (CO)	Results are mixed. Several studies report degraded performance on vigilance tasks following moderate CO exposure; other studies failed to detect effects of CO on vigilance, memory, or mathematical processing.	The effects of DISSUB-like CO exposure (<150 ppm exposure for up to 24 hours) on cognition are largely unknown.
Chlorine (Cl)	Cl exposure is associated with long-term deficits in memory, attention, psychomotor function, and problem solving.	The cognitive effects of Cl have only been examined post-accidental exposure; thus, the exact level of exposure that results in cognitive deficits and the time course for developing deficits following exposure are unknown.
Hydrogen chloride (HCl)	HCl is unlikely to directly impair cognition.	Research is needed to determine if DISSUB-like exposure (<35 ppm for up to 24 hours) could indirectly affect cognition due to secondary symptoms.
Hydrogen cyanide (HCN)	Exposure to high concentrations of HCN (higher than would be experienced in a DISSUB scenario) may cause mood changes.	The effects of HCN on objective functioning or at DISSUB-like concentrations (<15 ppm) are unknown.
Hydrogen sulfide (HS)	Only one study has experimentally investigated the cognitive effects of HS; results suggests that cognition may be affected.	Further research is required to replicate and expand on the results of that study.
Lithium hydroxide (LiOH)	There is no conclusive evidence to either support or refute that LiOH affects cognition.	The cognitive effects of LiOH have not been experimentally assessed.

Stressor	Summary of Key Findings	Knowledge Gap(s)
Nitrogen dioxide (NO_2)	There is no conclusive evidence to either support or refute that NO_2 affects cognition.	The effects of NO_2 have not been examined independent of other air contaminants.
Sulfur dioxide (SO_2)	There is no conclusive evidence to either support or refute that SO_2 independently affects cognition.	The effects of SO_2 have not been examined independent of other air contaminants.
Increased Compartment Pressure		
Increased oxygen partial pressure	Some evidence indicates increased oxygen partial pressure affects cognition, but most research has explored the effects of increased oxygen in conjunction with increased N_2 and CO_2.	Research is required to explore the independent effects of increased oxygen partial pressure on cognitive processes and under pressure conditions that would be likely during a DISSUB event.
Increased nitrogen partial pressure	The symptoms of nitrogen narcosis are widely compared to the effects of alcohol intoxication, including alterations to mood and cognition. Nitrogen narcosis develops at pressures near the maximum pressure reached during a survivable DISSUB scenario; thus it is unlikely to greatly affect survival efforts.	Research is required to examine whether nitrogen narcosis will be of operational significance in a DISSUB scenario, given that symptoms typically develop at partial pressures exceeding what would likely occur in a survivable DISSUB.
Lighting		
Dim lighting	Dim lighting can decrease individuals' ability to see their environment; prolonged exposure may result in decreased mood; short-term exposure may enhance performance of non-visual tasks.	Additional research is required to determine the exact cognitive effects using DISSUB-like dim lighting over the course of several days.
Red lighting	There is no conclusive evidence to either support or refute that red lighting affects cognition.	Research is required examining the effects of red lighting over multiple days.
Other Environmental Stressors		
Flooding	Total-body submersion in water may impair psychomotor function and memory; however, there no direct evidence to suggest that partial-body immersion independently affects cognition.	Research is required to delineate the cognitive effects of operating while submerged/immersed, effects of diving equipment, and exposure to cold.
Fire	Decision-making occurs rapidly when reacting to fires and is likely based on past experience rather than cognitive flexibility. Fire is unlikely to impact cognitive function.	There has been no research, to our knowledge, exploring the impact of fire on cognitive domains other than decision-making.

Stressor	Summary of Key Findings	Knowledge Gap(s)
Noise	There is no conclusive evidence to suggest that the low levels of ambient noise expected during a DISSUB would provide either a cognitive benefit or decrement.	Research is needed to determine the impact of DISSUB-like ambient noise on cognition.
Radiation	Much of what is known about the relationship between radiation exposure and cognition is related to long-term effects following acute exposure; radiation exposure is associated with impaired psychomotor function, memory, executive function, and reduced subject mental function, but reported impacts are correlational.	The effects of radiation have primarily been investigated following accidental exposure; therefore, the exposure levels that cause cognitive deficits and the time course of their development remain largely unknown. Ethical considerations will limit future studies.

Effects of DISSUB Mental Stressors

Confinement/Isolation

Under normal operational conditions, submariners must cope with the psychological stress of being in enclosed, confined spaces that are isolated from the surface world (e.g., Beare, Biersner, Bondi, & Naitoh, 1981). However, these effects are likely to be exacerbated in a DISSUB scenario due to further reductions in compartment space (e.g., flooding in other compartments) and increased isolation (e.g., no contact with rescue forces; Chabal et al., 2019).

The stress of prolonged confinement and isolation during normal submarine operations may lead to cognitive impairments (see Shobe et al., 2003 for a further discussion); however, empirical research conducted during normal submarine operations has typically failed to find any cognitive declines over the course of an underway (B. L. Bennett, Schlichting, & Bondi, 1985; Schlichting, Styer, & Gray, 1989; Weybrew, 1971). It is not clear whether this lack of cognitive decline is because confinement does not impair cognition or because the rigorous selection and training process creates submariners who are resistant to the effects of confinement (e.g., Theriaque & Schlichting, 1997; Trivette, Raigoza, & Gonzales, 2016). Studies conducted in confined/isolated environments similar to a submarine (e.g., spaceflight and polar winter-overs) have found evidence of cognitive impairments (e.g., Fowler, Bock, & Comfort, 2000; Mullin, 1960). However, these effects are not consistently observed across studies and may be attributable to other factors that would not be experienced in a submarine environment, such as weightlessness or differences in personality profiles and training (for recent review see Strangman, Sipes, & Beven, 2014).

A critical limitation in the majority of studies involving confinement is that they typically include small sample sizes. The experimental burden required for these studies (e.g., continuous supervision of participants, laboratory space utilization, etc.) and the fact that typically only a small number of participants can be confined at a time makes larger scale studies less practical (Shobe et al., 2003; Strangman et al., 2014). As such, these studies are often underpowered and not statistically reliable, which limits the ability to draw conclusions on the cognitive effects of confinement (Strangman et al., 2014).

While further research is required with confinement parameters more closely matching a DISSUB scenario and with larger sample sizes, laboratory studies may not be able to completely reveal the cognitive effects of confinement that submariners are likely to experience in a DISSUB scenario. Researchers have suggested that the effects of confinement are “primarily a source of inferences about what to expect” (Ruff, Levy, & Thaler, 1959, p. 604); therefore, laboratory studies of confinement, which will never be able to incite the motivation caused by the true danger experienced in a DISSUB scenario, may underestimate the cognitive effects.

Death of Shipmates

During a DISSUB scenario, submariners who survive the inciting event may be required to handle the dead bodies of fellow shipmates (NAVSEA, 2013b). Much of the literature on the effects of the handling of dead bodies has focused on risks associated with human health, specifically the risk of acquiring infectious diseases following exposure to bodies after natural disasters, rather than on cognitive impacts (e.g., Committee on the Future of Emergency Care in the United States Health System, 2007; O. Morgan, 2004; Watson, Gayer, & Connolly, 2007). While the smell from dead bodies generally does not pose any health risk in well-ventilated areas (Pan American Health Organization, 2016), this may be a concern in a submarine environment (particularly one engaged in a DISSUB scenario) that is not well ventilated. The potential health risks associated with death of shipmates will primarily vary based on whether submariners will be able to physically isolate the dead bodies.

The cognitive effects of handling dead bodies, specifically during military operations, is rarely discussed in the literature. Personal narratives are one of the few sources available that provide insight into the effects that individuals may experience when handling the dead. For example, Major Andrew J. DeKever, who processed and handled the bodies of those that died in combat, described the bodies as often being “blown apart,” “dismembered,” and/or “shredded.” He described the heavy emotional burden of this exposure, which affected his overall well-being and contributed to symptoms including difficulty eating, difficulty communicating with others, trouble sleeping, and continued mental anguish leading to multiple suicide attempts (DeKever, 2011). The handling of dead bodies during war has also been described as making soldiers emotionally numb (Judd, 2009). One account described a situation when a body was brought into a mortuary tent for the first time with a new team, and the soldiers “froze” and were unable to carry out job-related tasks despite ample training (Goodell & Hearn, 2008). Given that submariners are unlikely to have prior experience handling dead bodies, they may behave similarly when first faced with the death of their shipmates. The mental confusion and dissociation that can emerge when faced with tangible evidence of imminent death could impair survival efforts if survivors are unable to act appropriately and rapidly (Whybourn et al., 2019).

One factor that may reduce the psychological effect of handling dead bodies in a DISSUB scenario is the perceived severity of the situation. It has been suggested that when the disposal of bodies is made a significant priority, then the psychological burden is not as prominent (Pan American Health Organization, 2016). Submariners are likely to feel a sense of gravity and seriousness during a DISSUB scenario, and this sense of duty may reduce the psychological stress associated with handling dead bodies in the moment. It is possible that long-term psychological concerns, such as post-traumatic stress disorder (Biggs & Fullerton, 2014), could arise due to this; however, that is outside the scope of the current review as it is unlikely to have a direct impact on survival efforts.

Various avoidance strategies may also be effective in reducing the psychological burden of handling dead bodies. In a report by McCarroll, Ursano, Wright, and Fulerton (1993), interviews were conducted on personnel responsible for the clean-up of bodies after three violent events including the explosion of the USS Iowa in 1989, in which 47 sailors were killed. During clean-up, personnel were instructed to implement avoidance strategies, including “not looking at the face, not learning the names, and avoiding situations that ‘humanize’ the body” (McCarroll et al., 1993, p. 214). Those interviewed reported that intact bodies that were more immediately recognizable as human were more bothersome than those bodies with more wounds (McCarroll et al., 1993). Overall these strategies help individuals remain emotionally detached from the victims (DeKever, 2011; Krane, 2004).

These avoidance strategies are likely to be less effective in a DISSUB scenario in which the survivors handling the dead bodies will have known the deceased. The adversities of submarine life (e.g., extended isolation from the outside world and confinement while underway) foster a great sense of camaraderie among submariners who endure the unique environmental and occupational conditions together (Trivette et al., 2016). As a result, survivors will likely have some degree of emotional involvement when dealing with the bodies of the deceased and may experience periods of intense grief (Sumathipala, Siribaddana, & Perera, 2006). The ability to cope with handling the dead bodies of friends or fellow crew members is largely unknown.

Overall, there is a lack of scientific research to support or refute the existence of cognitive decrements associated with exposure to dead bodies. The little that we do know comes from personal narratives (e.g., DeKever, 2011), interviews with the small population of workers who respond to disaster events (e.g., McCarroll et al., 1993), and manuals for the handling of dead bodies (e.g., Hershiser & Quarantelli, 1976). Knowledge regarding the psychological and cognitive implications of the handling of dead bodies is all anecdotal, as experimental laboratory studies are impractical and unethical.

Hopelessness

Survivors during a DISSUB scenario may experience feelings of hopelessness regarding their current situation (Chabal et al., 2019), which can lead to a lack of will to live or to suicidal behavior (Lester, 2012). Periods of hopelessness begin with feelings of confusion followed by a slow realization of the secondary threats and fears that are present; negative feelings such as resentment, anger, and guilt can become present along with signs of amnesia (Golden & Tipton, 2002). Although the effects of hopelessness on cognition have not been well described in the literature, it has been reported that periods of hopelessness can result in complete cognitive shutdown and a resignation to death (Golden & Tipton, 2002).

In order to overcome these feelings of hopelessness, survivors of a DISSUB may use thoughts of their loved ones as a motivator to survive. There is clear agreement among submariners that prolonged separation from home and disconnect with family is one of the most difficult aspects of being underway (Kimhi, 2011); these feelings may pressure survivors to regain their willpower to live. Through anecdotal accounts, Golden (2002) concluded that, “the enhancement of the will to survive provided by the thought of loved ones, particularly children, appeared to be a common occurrence” (p. 240). Additionally, positive thinking, group coherence, and humor have been identified as important coping skills for periods of hopelessness that would reinforce resilience (Kimhi, 2011).

Boredom

Following any emergency response procedures in a DISSUB scenario (e.g., mitigating flooding or fire), submariners will be required to rest as much as possible and may experience extreme feelings of boredom (Chabal et al., 2019; NAVSEA, 2013b). Boredom is an emotional and psychophysical state that is distinct from similar constructs such as apathy or depression, and can loosely be defined as the inability to optimally allocate attentional resources towards the completion of a task (Bench & Lench, 2013; Goldberg, Eastwood, Laguardia, & Danckert, 2011). Because boredom is tied to attentional processes (Eastwood, Frischen, Fenske, & Smilek, 2012), it is most likely to impair performance on tasks requiring vigilance. Previous research has suggested that task-related boredom – as opposed to task overload – is the primary reason for failure to maintain vigilance (Pattyn, Neyt, Henderickx, & Soetens, 2008). This could have operational implications, as work-related boredom can jeopardize occupational safety during tasks that require vigilance, such as driving (Kass, Beede, & Vodanovich, 2010).

In spite of its known impacts on cognition, boredom is unlikely to have a direct impact on performance during a DISSUB event. This is because boredom will be most prevalent during periods of rest and not while submariners are performing essential tasks.

Conflict among Crew Members

Survivors in a DISSUB scenario may experience interpersonal conflict when making critical decisions such as whether to initiate escape or await rescue (Chabal et al., 2019). This conflict can potentially hinder survival efforts by negatively impacting how survivors communicate amongst themselves and to rescue assets.

Interpersonal conflict results in communication that is less complex and more constrained (Sillars & Parry, 1982). In the event that these communication difficulties result in hostility among crew members, survivability will be severely challenged (Kanas, 2005; Kraft, Lyons, & Binder, 2003; Seymour, 1970). In a worst case scenario, physical altercations between those trapped onboard the DISSUB may result in submariners' injury or death.

Conflict among crew members may also negatively impact how survivors communicate with rescue assets. In a confined environment such as a DISSUB, feelings of anger and hostility may be displaced onto outside entities who are not confined with the group, such as the rescue forces with whom the group is trying to communicate (Kanas, 2005; Palinkas, 2007; Sillars & Parry, 1982). This displacement of anger is believed to serve as an outlet to prevent negative emotions from being directed toward those that are in close proximity (Palinkas, 2001).

Overall, if the effects of interpersonal conflict are not mitigated (e.g., through the use of coping strategies such as humor and increased psychological support; Kimhi, 2011; Van Wijk & Cia, 2016) survival efforts in a DISSUB scenario may be negatively affected. Submarine crews may benefit from training in conflict management in order to ensure that they are able to maintain effective team functioning even under conditions of isolation and stress (Kass et al., 2010).

Mental Stressors Conclusions

The key findings for each environmental stressor are summarized in Table 3, as well as knowledge gaps for how these findings may generalize to a DISSUB scenario. Other than causing decreases in mood, there is little evidence that mental stressors will directly impair cognitive function. While decreased mood may lead to breakdown in communication and increase interpersonal tensions, this cognitive domain does not directly degrade performance of tasks. Of all the mental stressors, boredom is the only one that has been tied to decreased performance on vigilance tasks. However, in a DISSUB scenario, boredom will most likely set in during periods of rest and not when submariners are performing essential tasks. Due to ethical and logistical constraints, it is unlikely that empirical studies of cognitive effects of these mental stressors under DISSUB-like condition are possible.

Table 3: Summary of key findings and knowledge gap(s) for mental stressors.

Stressor	Summary of Key Findings	Knowledge Gap(s)
Confinement/isolation	Empirical research conducted in submariners during normal operations has largely failed to find effects of confinement on cognitive performance.	The effects of DISSUB-like confinement should be further researched using submarine-qualified individuals who are likely more resilient to effects of confinement.
Death of shipmates	Death of shipmates will likely decrease mood; there is a lack of scientific evidence to either support or refute cognitive decrements in other domains.	Due to logistical and ethical constraints, there is no experimental research examining the effects of shipmate death on objective cognitive function.
Hopelessness	Hopelessness will decrease mood; extreme hopelessness could result in complete cognitive shutdown and resignation to death.	Due to logistical and ethical constraints, there is no experimental research examining the effects of hopelessness on objective cognitive function.
Boredom	Boredom may impair vigilance, but is unlikely to have a direct impact on performance during a DISSUB event.	While the effects of boredom on cognition are generally well-described, further research is required to quantify the prevalence of boredom in order to determine its potential operational impact.
Conflict among crew members	Interpersonal conflict may result in miscommunication among survivors; there is no evidence to suggest conflict directly impairs cognition.	Due to logistical constraints, there is no experimental research examining the effects of crew conflict on objective cognitive function.

Effects of DISSUB Physical Stressors

Pain/Injury

During the course of a DISSUB scenario, a portion of survivors may experience intermittent or ongoing pain due to burn trauma, musculoskeletal injuries, headaches, and/or hunger pains (Chabal et al., 2019; DeMers, Horn, & Hughes, 2009; Whybourn et al., 2019). A substantial body of research has investigated the relationship between pain and cognitive impairment in clinical populations with chronic pain (i.e., pain lasting for more than six months), such as those with fibromyalgia (Luerding, Weigand, Bogdahn, & Schmidt-Wilcke, 2008), chronic back pain (Apkarian et al., 2004), diabetes mellitus (Roberts et al., 2008), postherpetic neuralgia (Pickering & Leplege, 2011), or cervical pain (Roth, Geisser, Theisen-Goodvich, & Dixon, 2005). These studies have found a wide range of cognitive deficits associated with chronic pain, including impairments in attention (Grisart & Plaghki, 1999), processing speed (Hart, Martelli, & Zasler, 2000), decision making (Apkarian et al., 2004), working memory (Dick & Rashiq, 2007), and executive function (J. M. Glass et al., 2011). However, examining the effect of pain on cognitive functioning in clinical populations introduces interpretational difficulties, as cognitive deficits may be attributed to factors other than the presence of pain (e.g., influence of medication, motivation to pursue litigation, etc.; Tait, Chibnall, & Richardson, 1990), or deficits may develop as a general effect of condition pathology (Boone, 2007; Moriarty, McGuire, & Finn, 2011). Therefore, this review focuses on the effects of acute pain on cognitive function in non-pathological control subjects; these studies are most representative of the population and type of pain that submariners may experience in a DISSUB scenario.

Several cognitive models of pain processing have postulated a close relationship between attentional processes and pain perception (Eccleston & Crombez, 1999; Leventhal & Everhart, 1979; Price & Harkins, 1992). The purpose of injury-related pain is believed to be to communicate the body’s physiological needs to an organism (i.e., need for rest and recovery; Hadjistavropoulos et al., 2011); therefore, pain perception requires attentional resources and may interfere with performance on tasks requiring sustained attention. In a study by Lorenz and Bromm (1997), healthy young adults experienced acute musculoskeletal pain induced by an ischemic upper arm tourniquet while performing a memory search task and an auditory oddball task. Performance on the memory search task was worse when participants were experiencing pain compared to a control condition, suggesting that pain and attention competed for limited cognitive resources. Similarly, a reduced P300 amplitude (an attention-related event-related potential component) was observed during the auditory oddball task when participants were in pain. This suggests that the presence of pain decreased the allocation of resources to the cognitive task, resulting in a reduction in the encoding of the stimuli and less salient difference between the two stimuli.

In further support of the theory that pain and attention compete for finite shares of cognitive resources, pain intensity resulting from thermal (Bantick et al., 2002) or electrical stimulation (Seminowicz & Davis, 2007) is reduced when participants are engaged in attention-demanding tasks. A similar relationship has been observed between attention and pain in individuals experiencing chronic musculoskeletal pain (Eccleston, 1994; Kewman, Vaishampayan, Zald, & Han, 1991).

Evidence suggests that headache-related pain may have a similar effect on attentional processes. Of the 47.9% of participants in SURVIVEX 2004 (a simulated disabled submarine scenario) that reported experiencing headache, 60.0% reported that their headache interfered with their ability to concentrate on tasks (Horn et al., 2009). Though no cognitive tests were performed as a part of SURVIVEX, experimental studies support these subjective findings (Attridge, Edmund, & Christopher, 2016; Moore, Keogh, & Eccleston, 2013). Interestingly, both Attridge (2016) and Moore (2013) found that self-reported headache intensity was not related to the magnitude of observed cognitive impairment; this suggests that even a mild headache can impair cognitive performance.

Analgesics are available in First Aid kits aboard the submarine and could potentially be used to mitigate the effects of pain. However, the specific medication used may itself have an impairing effect on cognitive functioning (S. L. Chapman, Michael, & Barbara, 2002). For example, short-term opioid use can result in subjective symptoms of mental confusion and grogginess often accompanied with deficits in psychomotor and vigilance tasks (Westerling, Frigren, & Höglund, 1993; Zancy, 1995). It is not known what the net effect of analgesic medication and pain relief would be for survivors in a DISSUB scenario experiencing varying degrees of pain from musculoskeletal trauma, burns, or headaches.

Overall, pain is a highly-salient percept that draws an individual's attention. As such, the presence of pain is likely to draw cognitive resources away from a task, resulting in slowed and impaired task performance. While countermeasures for pain perception can be applied in the form of analgesic medication, the specific medication used may itself have an impairing effect on cognitive functioning.

Nutrition

During a DISSUB scenario, survivors must subsist upon a low-calorie, high-fat diet intended to limit CO_2 production (Chabal et al., 2019; NAVSEA, 2013b). The effects of caloric restriction and a high-fat diet on submariner cognition are reported separately.

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., Bolton, Burgess, Gilbert, & Serpell, 2014; Pender, Gilbert, & Serpell, 2014). However, almost as many studies have failed to find any effects of short-term fasting in those same cognitive domains (e.g., Benton & Parker, 1998; Lieberman et al., 2008; Sünram-Lea, Foster, Durlach, & Perez, 2001; Yasin, Khattak, Mamat, & Bakar, 2013).

One issue that has made it difficult to determine the effect of caloric restriction on cognition is the historic lack of participant blinding across studies. Many researchers have made observations during periods of religious fasting (e.g., Doniger, Simon, & Zivotofsky, 2006; Yasin et al., 2013) or have instructed participants to skip meal(s) before coming into the laboratory for testing (e.g., Green, Elliman, & Rogers, 1995; Green, Elliman, & Rogers, 1997). In both instances, participant expectations may affect results. Popular claims that skipping meals has negative cognitive consequences (e.g., claims that breakfast is most important meal of the day) can influence participant perception and their subsequent performance on cognitive assessments (e.g., Jadad et al., 1996). Moreover, participants may consume additional food prior to fasting in order to "stock up" on energy (e.g., Ziaee et al., 2006), thereby altering the condition that the body is in prior to the caloric restriction (e.g., increased fat and glycogen stores) and potentially modulating the effects of short-term caloric restriction.

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 (see Insufficient Water Intake section, p. 32) or the interaction between caloric restriction and dehydration.

Finally, participant activity levels during fasting may also modulate the effects of caloric restriction on cognition (Maille & Schradin, 2017). If cognitive impairments during periods of caloric restriction reflect an energy-saving mechanism, then physical activity may impact the relationship between caloric restriction and cognition because physical activity is a competing source of energy expenditure. In some studies, participants continued with their regular routines while fasting (e.g., 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 (e.g., Landers, Arent, & Lutz, 2001; Tian et al., 2011). Neither of these situations is representative of individuals in a DISSUB scenario, in which submariners' physical activity will be 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 warrants further research (for recent review see Cherif, Roelands, Meeusen, & Chamari, 2016).

Overall, the effects of caloric restriction on cognition are not well understood. Dedicated research that explores caloric restriction under the specific circumstances expected during a DISSUB scenario (unexpected, prolonged fasting under conditions of limited physical activity) is warranted.

High-fat diet. Large-scale cross-sectional studies have associated long-term consumption of high-fat diets with increased prevalence of cognitive impairment and decline (e.g., Eskelinen et al., 2008). While the correlational nature of this association precludes the drawing of causal conclusions, recent experimental research has indicated that even short-term exposure (i.e., four to seven days) to high-fat diets has the potential to impair cognitive functioning (Holloway et al., 2011). Rodent studies have indicated that high-fat diet consumption 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 and colleagues (2011) found that after five days of a diet in which 70% of calories came from fat, 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, Stevenson, Oaten, & Francis, 2017; 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 the impairment of glucose regulation resulting in insufficient glucose transportation to the brain (Cordner & Tamashiro, 2015). This may impair cognitive function because glucose is an essential energy source for supporting cognitive processes (DeCarli et al., 1995; Gold, 1995). Another proposed process is that alterations to synaptic plasticity obstruct the hippocampal operations 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, Poff, & Dean, 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 (Derrick et al., 2019), 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 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' abilities to recall information from previous trainings or learn how to operate unfamiliar escape equipment. However, if submariners enter nutritional ketosis then they may be more cognitively resilient against the effects of oxygen toxicity and hypoxia (D'Agostino et al., 2019; Zhao et al., 2017).

Insufficient Water Intake

Survivors in a DISSUB scenario may become dehydrated primarily due to restrictions in potable water and elevations in compartment temperature that increase sweat output (Chabal et al., 2019). While it is generally accepted that dehydration has a deleterious effect on cognition (e.g., Cian et al., 2000; Ganio et al., 2011; Grandjean & Grandjean, 2007), 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, Golightly, Field, Butler, & van Reekum, 2014).

Numerous studies have observed decreases in reaction time accuracy and/or increases in reaction time latency when individuals are dehydrated (Baker, Conroy, & Kenney, 2007; Cian, Barraud, Melin, & Raphel, 2001; Ganio et al., 2011), and there is evidence that these deficits begin at mild degrees of dehydration (1-2% of mass lost through body water; D'Anci et al., 2009). 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, Schachinger, Arnaud, Linder, & Keller, 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 and colleagues (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., 2000; A. V. Patel, Mihalik, Notebaert, Guskiewicz, & Prentice, 2007). In contrast, other studies have found no effect (D'Anci et al., 2009) or sometimes even an improvement in short-term memory performance when dehydrated (Tomporowski, Beasman, Ganio, & Cureton, 2007).

Research on working memory has been more consistent in its findings. Sharma and colleagues (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 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 and colleagues (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 our 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 and colleagues (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, clear-headedness, 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; A. V. 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., 2009). D’Anci and colleagues (2009) separated performance on a 15-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 past research 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 way 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, Audiffren, & Denjean, 2006; Maughan, Shirreffs, & Watson, 2007). This could be the reason that Tomporowski and colleagues (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 and colleagues (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 in these specific cognitive domains were found between dehydration methods, 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 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 and colleagues (Lindseth, Lindseth, Petros, Jensen, & Caspers, 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 any compensatory mechanism(s) may not have been sufficient to overcome chronic deficits. However, this 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.

In the event that DISSUB survivors become dehydrated and suffer cognitive consequences, it is possible that rehydration can rapidly restore cognitive performance. To date, however, the manner and time course in which rehydration may alleviate cognitive dysfunction remains relatively unexplored (e.g., Bandelow et al., 2010; Choma, Sforzo, & Keller, 1998; Masento et al., 2014; Wong, Sun, Huang, & Chen, 2014). 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, 2012). To circumvent this issue, maintaining adequate hydration should be a priority in a DISSUB scenario. In addition to the designation of an individual tasked with keeping individuals hydrated (NAVSEA, 2013b), submariners should pay attention to their urine color, which is a valid and sensitive field measure of overall hydration status (Armstrong et al., 1994; Armstrong et al., 1998).

Caffeine Withdrawal

Knapik and colleagues (2016) reported that approximately 87% of active duty Navy and Marine Corps service members consume caffeine regularly. While this prevalence of caffeine use is similar to that reported in the general population (80-90%), Knapik and colleagues (2016) also reported that service members consumed more daily caffeine than civilians. In a DISSUB scenario, caffeine use will be highly limited or unavailable (Chabal et al., 2019), and abrupt cessation of caffeine after habitual use may cause withdrawal symptoms (for a review see Sajadi-Ernazarova & Hamilton, 2019).

The most frequently-reported effect of caffeine withdrawal is headaches (Juliano & Griffiths, 2004; Rogers et al., 2005; Silverman, Evans, Strain, & Griffiths, 1992), which can manifest following overnight cessation of caffeine consumption (Lane & Phillips-Bute, 1998; Rogers et al., 2005) and may last up to a week (Griffiths et al., 1990; Hofer & Battig, 1994; van Dusseldorp & Katan, 1990). As noted in the section on Pain/Injury (see page 28), headaches from caffeine withdrawal, as with other forms of pain, are likely to draw cognitive resources away from a task, resulting in decreased performance.

Caffeine withdrawal also has a number of negative effects on subjective ratings of mood. 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, James, & Hogan, 2007; Lane & Phillips-Bute, 1998; Mills, Boakes, & Colagiuri, 2016; Rogers, Heatherley, Mullings, & Smith, 2013; Sigmon, Herning, Better, Cadet, & Griffiths, 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 4-7 Hz) following caffeine cessation may be the cause (H. E. Jones, Herning, Cadet, & Griffiths, 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).

In subjective studies of cognitive performance after caffeine cessation, individuals have reported decreases in mental alertness, ability to concentrate, clear-headedness, and vigor, as well as increased perceived difficulty when performing cognitively-demanding tasks (H. E. 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 have been documented when participants are administered a placebo under double-blind conditions as well as when participants are told they have consumed caffeine when they actually have not (Mills et al., 2016). The magnitude of these self-report symptoms are 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., 2013; Rogers, Richardson, & Elliman, 1995; Silverman et al., 1992).

In addition to self-report studies, many researchers have objectively measured cognitive performance after abrupt caffeine cessation, as would be expected in a DISSUB scenario. In a 2004 critical review of caffeine withdrawal, Juliano and Griffiths reported that 11 of 23 (48%) experimental studies that assessed performance with objective measures during caffeine cessation found degradation in performance on attention/vigilance tasks including finger tapping, visual vigilance, reaction time, symbol substitution, character recognition, and complex problem solving (Juliano & Griffiths, 2004). Researchers have reported that caffeine-withdrawn individuals 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, Ripley, Davies, Rusted, & Rogers, 2002). Furthermore, performance of caffeine-withdrawn individuals degrades more rapidly over the duration of a vigilance task than those who are not in caffeine withdrawal, suggesting caffeine withdrawal may make individuals more susceptible to time-on-task fatigue (Lane & Phillips-Bute, 1998; Rogers et al., 2013). While there are some studies that have failed to detect a degradation in attention/vigilance performance due to caffeine withdrawal, some of those results may be 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.

Researchers have yet to establish a clear understanding of caffeine withdrawal on memory. While Rogers and colleagues (2013) found that individuals experiencing caffeine withdrawal performed significantly poorer on a memory recognition task when required to remember changing sets of information, other studies have found no evidence for memory impairments following caffeine cessation using memory tasks such as simple word recall (H. E. Jones et al., 2000; Rogers et al., 2005). Thus, 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 another (Streufert et al., 1995) found impairments in abstract complex thinking associated with caffeine withdrawal. Conversely, however, Lyvers, Brooks, and Matica (2004) found no 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 individuals 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 (H. A. Jones & Lejuez, 2005; Waldeck & Miller, 1997), and the combined stress of the DISSUB scenario and caffeine withdrawal may further bring out heightened impulsivity (Lejuez et al., 2002; Lighthall, Mather, & Gorlick, 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.

In summary, caffeine withdrawal is associated with a degradation in a number of cognitive domains that may impact functioning during a DISSUB scenario. Documented degradations in attention/vigilance (e.g., Juliano & Griffiths, 2004) and decreases in clear-headedness and the ability to concentrate (e.g., Silverman et al., 1992) may disrupt individuals' abilities to effectively follow complicated and unfamiliar protocols when executing escape procedures. Decreases in friendliness and amicability (e.g., Lane & Phillips-Bute, 1998) may contribute to breakdown in command among survivors, and decreases in mental alertness and sustained attention (e.g., Rogers et al., 2005) may disrupt the senior survivor's 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 they should initiate an escape rather than wait for rescue). While the effects of caffeine withdrawal can be reversed within an hour of re-administering caffeine (Goldstein, Kaizer, & Whitby, 1969), the exact relationship between caffeine re-administration dose and alleviation of caffeine withdrawal symptoms on mood and cognitive functioning warrants further research. In a DISSUB scenario it may be important to prioritize the allocation of caffeine rations to caffeine-habituated individuals performing the most cognitively-demanding tasks in order to optimize their performance.

Fatigue

Despite ample opportunity for rest, survivors in a DISSUB scenario are likely to experience sleep loss and fatigue (Chabal et al., 2019). While fatigue is prevalent among submariners underway (Blassingame, 2001), it is likely to become exacerbated during a DISSUB scenario as the result of acute sleep deprivation (being awake >24 hours) due to the actions needed to mitigate any hazards at the onset of the inciting event. Chronic sleep deprivation may also emerge due to an increase in stress hormones or exposure to multiple stressors (Chabal et al., 2019; Meerlo, Sgoifo, & Suchecki, 2008).

Of the potential stressors present in a DISSUB scenario, the effects of fatigue on cognition are perhaps the most well-known (for comprehensive reviews see Banks & Dinges, 2007; Chabal et al., 2018; Durmer & Dinges, 2005; Killgore, 2010; Walker, 2008). Physiology and neuroscience research has suggested that the prefrontal cortex, an essential center for cognitive processing, is particularly susceptible to the effects of fatigue (Drummond et al., 1999; Munch et al., 2004; Thomas et al., 2000). For this reason, even mild sleep deprivation has a significant effect on cognition: sleep deprivation has been shown to negatively impact nearly every cognitive domain including attention/vigilance (Banks, Van Dongen, Maislin, & Dinges, 2010; Belenky et al., 2003; Henelius et al., 2014; Vgontzas et al., 2004), executive functioning (Couyoumdjian et al., 2010; Drummond, Paulus, & Tapert, 2006; Sallinen et al., 2013), decision making (Acheson, Richards, & de Wit, 2007; Killgore, Balkin, & Wesensten, 2006; Killgore, Kamimori, & Balkin, 2011; Killgore et al., 2007), and memory (Walker, 2009; Yoo, Gujar, Hu, Jolesz, & Walker, 2007). These performance deficits are accompanied by changes in mood and affect (e.g., Killgore et al., 2011), such as increased anger, negative thinking, decreased motivation, difficulty with delay of gratification, and increased impulsivity (Kahn-Greene, Lipizzi, Conrad, Kamimori, & Killgore, 2006; Kamphuis, Meerlo, Koolhaas, & Lancel, 2012; Killgore et al., 2008; Sicard, Nationale, Jouve, & Blin, 2001), all of which can decrease survivability in a DISSUB scenario.

Killgore and colleagues (2006) found that sleep-deprived individuals completing a gambling task made higher-risk decisions that provided short-term rewards but ultimately resulted in poorer long-term performance. This suggests that, in a DISSUB scenario, fatigued survivors may be more inclined to make riskier decisions, such as initiating an escape when they should instead wait for rescue. In fact, even well-trained military members are not impervious to fatigue-related increased impulsivity and risk-taking. A study of Navy helicopter pilots found that self-assessed impulsivity was higher following a strenuous overnight maritime counter-terrorism exercise relative to baseline data recorded prior to the mission (Sicard et al., 2001). Though the combination of factors in an operational scenario (e.g., fatigue, operational stress) make it difficult to pinpoint the precise cause of observed changes in impulsivity, these conditions are similar to what submariners will likely experience in a DISSUB scenario in which they are likely to experience the combined effects of fatigue and operational stress (Chabal et al., 2019). Although fatigued individuals may be aware that they are susceptible to decrements in cognitive performance (Banks et al., 2010; Vgontzas et al., 2004), they may not be able to identify when they are impaired or self-assess their degree of cognitive impairment (Sallinen et al., 2013; Van Dongen, Maislin, Mullington, & Dinges, 2003). If fatigued individuals during a DISSUB scenario cannot determine their own level of impairment, they may not know when or if they should pass on cognitive tasks, such as decision making, to less sleep deprived individuals.

Though the relationship between sleep deprivation and cognitive dysfunction is not perfectly linear, in general, more sleep deprivation results in more degraded performance, with even mild sleep deprivation impacting cognitive function. During chronic sleep deprivation, cognitive impairment emerges when individuals get less than seven hours of sleep per night, and cognitive impairments become more pronounced with each subsequent day of suboptimal sleep duration (Belenky et al., 2003; Haavisto et al., 2010; Van Dongen et al., 2003; Vgontzas et al., 2004). Furthermore, the cognitive impairments associated with chronic sleep deprivation are not corrected following a single night of optimal sleep duration; recovery takes multiple days depending on the severity and duration of the chronic sleep deprivation (Banks et al., 2010). The fatigue levels of key decision-makers during a DISSUB scenario should therefore be closely monitored.

Poor Hygiene

Due to a loss in power and prioritization of water for drinking during a DISSUB scenario, submariners will likely be exposed to conditions of poor sanitation (e.g., disabled plumbing system, limited bathing opportunities, exposure to decomposing bodies) and will develop poor hygiene (Chabal et al., 2019). Poor hygiene is associated with a number of health issues including increased rates of infection, dental disease, and diarrhea (Bartram, Lewis, Lenton, & Wright, 2005; Ejemot-Nqadiaro, Ehiri, Meremikqu, & Crichley, 2008; Franco et al., 1989). However, little is known about how poor hygiene may causally affect cognitive functioning. While poor hygiene is commonly recognized as an element of self-neglect common in cognitively-impaired clinical populations such as those with schizophrenia, depression, or dementia (Burnett, Coverdale, Pickens, & Dyer, 2007; C. B. Dyer, Goodwin, Pickens-Pace, Burnett, & Kelly, 2007; Gopinath & Chaturvedi, 1992; Lukoff, Liberman, & Neuchterlein, 1986), in these cases, poor hygiene is a consequence of mental illness and cognitive impairment rather than the cause of it.

One potential way poor hygiene may impact cognition is indirectly, through the development of sepsis, a life-threatening condition in which the immune response to infection causes damage to tissues and organs (Nguyen et al., 2006). Several studies have found that a portion of sepsis survivors develop lasting cognitive impairment (Iwashyna, Ely, & Smith, 2010; Yende & Angus, 2007). However, these are long-term impacts; sepsis due to poor hygiene would emerge after weeks or months, and is not likely to affect operations during the onboard survival phase of a DISSUB scenario.

While little is known about the acute effects of poor hygiene practices on cognition, poor hygiene has the potential to predispose individuals to other stressors that are known to affect cognition. For example, improper disposal of human waste, exposure to decomposing bodies/body parts, improper handwashing, and compromised food safety can all lead to diarrhea (Cairncross et al., 2010; Conly & Johnston, 2005; Curtis, Cairncross, & Yonli, 2000; Ejemot-

Nqadiaro et al., 2008; Scott, 2003), which may cause cognitive deficits related to dehydration to emerge (see Insufficient Water Intake section, p. 32; Liebelt, 1998). However, there is insufficient evidence to support or refute the claim that acute poor hygiene in a DISSUB scenario will independently affect submariners' cognition.

Physical Stressors Conclusions

The key findings for each physical stressor are summarized in Table 4, as well as knowledge gaps in how these findings may generalize to a DISSUB scenario. Overall, evidence indicates the physical stressors of pain/injury, caffeine withdrawal, and fatigue will negatively affect cognitive functioning during a DISSUB scenario. Additionally, research suggests that a high-fat diet may impair cognition after a period of several days. Results are mixed with regard to caloric restriction and insufficient water intake on cognitive functioning during a DISSUB scenario. Current research in these areas has not investigated the effects of these stressors under DISSUB-like conditions (i.e. constant or near-constant exposure over the course of several days). The lack of experimental work investigating poor hygiene as a factor precludes concluding whether poor hygiene is likely to affect cognitive functioning in a DISSUB scenario.

Table 4: Summary of key findings and knowledge gap(s) for physical stressors.

Stressor	Summary of Key Findings	Knowledge Gap(s)
Pain/injury	Acute pain/injury and attentional processes compete for cognitive resources; thus pain may impair performance on attentional tasks Analgesics used to mitigate the effects of pain may, themselves, affect cognition.	The effects of pain on cognitive domains other than attention/vigilance are less well known. Determining the net effects of pain and analgesic use on cognition requires further research.
Nutrition (caloric restriction)	Results on the effect of caloric restriction on cognitive function are mixed, with some detecting impairment across cognitive domains and others failing to detect any impairment; in addition, results vary based on degree/duration of restriction and activity levels.	Further research on the effects of caloric restriction in DISSUB-like conditions (i.e. over the course of multiple days in sedentary individuals) is required.
Nutrition (high-fat diet)	A high-fat diet is likely to impair memory and learning processes over the course of 3-5 days; however, if submariners enter a nutritional ketosis state (due to high-fat, low-carb diet), ketogenic cognitive resilience may counteract performance degradations due to hypoxia or oxygen toxicity	The combined effects of a DISSUB-like diet, which is both high-fat and low-calorie, are largely unknown. Research is needed to determine if and when a DISSUB-like diet will induce ketosis, and how that may impact cognitive functioning.

Stressor	Summary of Key Findings	Knowledge Gap(s)
Insufficient water intake	While there is evidence to suggest that acute dehydration impairs cognition, compensatory mechanisms may mask cognitive decrements; the effects of long-term dehydration (i.e. several days) on cognition are not well understood.	Research is needed to determine the specific cognitive domains that are likely to be affected by chronic dehydration.
Caffeine withdrawal	Caffeine withdrawal causes deficits in attention/vigilance, subjective cognitive functioning, and increased irritability.	The effects of caffeine withdrawal on objective cognitive domains other than attention/vigilance, including memory and impulsivity, require further replication and research.
Fatigue	Fatigue has profound effects on cognition including deficits to attention/vigilance, executive functioning, decision making, memory, and increased irritability.	While the effects of fatigue on cognition are well-described, further research is required to quantify the extent of fatigue and sleep-deprivation submariners are likely to experience in a DISSUB scenario.
Poor hygiene	There is no conclusive evidence to either support or refute that poor hygiene directly effects cognitive functioning.	Further research is required to determine whether acute poor hygiene will independently affect submariner cognition.

Conclusions

This is the second report in a two-part series that identifies stressors that may be present in a DISSUB scenario, reviews the potential cognitive effects of these stressors, and considers how these cognitive effects could impair submariner operations during the onboard survival phase. In this report, we reviewed how specific environmental, mental, and physical stressors in a DISSUB scenario can affect a submariner's cognitive function. Overall, we reviewed 23 environmental stressors (in the categories of thermal, atmospheric gas composition, air contaminants, lighting, flooding, fires, noise, and radiation), five mental stressors, and six physical stressors. These particular stressors were selected because of their possible presence during a DISSUB event and their potential effects on cognition. We reviewed these stressors with particular focus on how they may affect the following cognitive domains: psychomotor function, attention/vigilance, memory, mathematical processing, cognitive flexibility, risk-taking/impulsivity, and mood. Similar to how we selected the stressors to review, we chose to focus on these cognitive domains given their importance in a DISSUB scenario in which submariners will have to perform critical tasks and procedures such as reacting to emergencies, conducting stay time calculations, and making critical decisions about whether to execute an escape or wait for rescue assets to arrive. Table 5 summarizes which stressors are likely to affect each of these highlighted cognitive domains. While some of these stressors, such as temperature changes, fatigue, and caffeine withdrawal, have strong evidence to suggest they will impact several cognitive domains, many others have not been studied under DISSUB-like conditions. Therefore, the absence of a stressor under a particular cognitive domain does not mean that it does not affect that domain. Rather, it is more likely that the relationship between a stressor and a particular cognitive domain has not been objectively investigated. Specifically, relatively few stressors have been examined with regard to their effect(s) on mathematical processing, cognitive flexibility, and risk-taking/impulsivity. Thus, there is a need for more research on how different stressors will impact cognitive function and survival in a DISSUB scenario. In addition to the summary in Table 5, more specific key findings are summarized for each stressor and knowledge gaps are highlighted in Tables 2-4.

In Table 6, we have synthesized our findings from both reports to categorize the stressors based on their likelihood of affecting survival in a DISSUB scenario. The five categories are:

1. Stressors that may affect cognition but are unlikely to occur during a DISSUB scenario;
2. Stressors that are likely to occur but are not likely to significantly affect cognition/survival efforts;
3. Stressors that will affect cognition between 2 and 7 days after the DISSUB inciting event;
4. Stressors that will affect cognition within the first few hours or day of the DISSUB inciting event;
5. Stressors for which there is insufficient information at this time to categorize.

For example, while boredom is likely to occur and has effects on cognition, it is most likely to be prevalent among survivors not carrying out operational duties; therefore, the effects of boredom are not likely to affect survival efforts, and boredom is classified under category 2. Additionally, some stressors are dual-categorized. For example, conflict among crew members could occur immediately following the inciting event if submariners perceive an individual as being at fault (Chabal et al., 2019); however, conflict among crew members could also develop multiple days after the inciting event due to increased irritability among submariners experiencing fatigue, caffeine withdrawal, caloric restriction, etc. (Chabal et al., 2019). Therefore, conflict among crew members is categorized under both 3 and 4.

It is likely that cognitive impairments will be compounded when more than one is present. For example, we hypothesize that stressors in combination (e.g., fatigue, increased temperature, changes in atmospheric composition, and pain) will have a greater impact on cognition than any of these individual stressors alone. Given the many different stressors that will be present in a DISSUB, it will be extremely difficult, if not impossible, to study these stressors in different combinations to conclusively determine combined effects. However, our review and summary of the independent impacts provides a comprehensive summary of the known impacts of these stressors on cognition and highlights key knowledge gaps areas where future research is required.

Table 5: List of stressors which are known to affect each cognitive domain. Stressors for which there is strong evidence to support that they are likely to affect cognition (i.e., multiple studies supporting the claim) are in bold. Other listed stressors have some evidence to support that they have an effect, but findings may be equivocal across studies. NOTE: The absence of a stressor under a particular cognitive domain does not necessarily indicate we can definitively refute the effects of that stressor on that cognitive domain.

Psychomotor function	Attention/ vigilance	Memory	Mathematical processing	Decision Making		Mood
				Cognitive flexibility	Risk taking/impulsivity	
- Thermal (decreased temperature) - Atmospheric gas composition (decreased oxygen levels) - Air contaminants (chlorine) - Flooding - Radiation	**- Thermal (increased temperature and decreased temperature)** - Atmospheric gas composition (decreased oxygen and increased carbon dioxide) - Air contaminants (NH_3, CO, Cl) **- Boredom** **- Pain/injury** - Nutrition (caloric restriction) - Insufficient water intake **- Caffeine withdrawal** **- Fatigue**	**- Thermal (increased temperature and decreased temperature)** - Atmospheric gas composition (decreased oxygen) - Air contaminants (NH_3, CL, NO_2) - Flooding - Pain/injury - Nutrition (caloric restriction and **high-fat diet**) - Insufficient water intake - Caffeine withdrawal **- Fatigue**	- Thermal (increased temperature) - Atmospheric gas composition (decreased oxygen and increased carbon dioxide) - Increased pressure (nitrogen partial pressure)	- Thermal (decreased temperature) - Atmospheric gas composition (increased carbon dioxide) - Fire - Pain/injury - Caffeine withdrawal - Fatigue	- Thermal (increased temperature) **- Increased pressure (nitrogen partial pressure)** - Lighting (dim lighting) **- Fatigue**	**- Thermal (increased temperature)** - Atmospheric gas composition (decreased oxygen and increased carbon dioxide) - Air contaminants (HCN, SO_2) **- Increased pressure (nitrogen partial pressure)** - Lighting (**dim lighting** and red lighting) **- Death of shipmates** **- Conflict among crewmembers** **- Insufficient water intake** **- Caffeine withdrawal** **- Fatigue**

Table 6: Categorization of the stressors based on their likelihood of affecting survival in a DISSUB scenario. These results reflect the synthesis of information from Report 1 in the series (Chabal et al., 2019) and the present report.

	Stressors that may affect cognition but are unlikely to occur during a DISSUB scenario	**Stressors that are likely to occur but are not likely to significantly affect cognition/survival efforts**	**Stressors that will affect cognition between 2 and 7 days after the DISSUB inciting event**	**Stressors that will affect cognition within the first few hours or day of a DISSUB inciting event**	**Stressors for which there is insufficient information at this time to categorize**
Environmental stressors	- Thermal (decreased temperature) - Increased pressure (increased nitrogen partial pressure) - Radiation - Increased pressure (increased oxygen partial pressure)	- Flooding - Noise	- Thermal (increased temperature) - Atmospheric gas composition (decreased oxygen and increased carbon dioxide) - Air contaminants (hydrogen sulfide) - Lighting (dim lighting)	- Air contaminants (hydrogen sulfide)	- Thermal (increased humidity) - Air contaminants (all except for hydrogen sulfide) - Fire - Lighting (red lighting)
Mental stressors		- Boredom	- Hopelessness - Death of Shipmates - Conflict among crew members	- Death of Shipmates - Conflict among crew members	- Confinement and isolation
Physical stressors			- Pain/injury - Nutrition (caloric restriction and high-fat diet) - Insufficient water intake - Fatigue	- Pain/injury - Caffeine withdrawal	- Poor hygiene

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