Naval Submarine Medical Research Laboratory

NSMRL/F1705/TR--2021-1351 September 7, 2021

Cognitive and Operational Performance During a Five-Day Disabled Submarine Simulation

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*: 07-09-2021

2. REPORT TYPE: Technical Report

3. DATES COVERED *(From - To)*: 1 OCT 2017 - 30 SEPT 2020

4. TITLE AND SUBTITLE

Cognitive and Operational Performance During a Five-Day Disabled Submarine Simulation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER: F1705

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8. PERFORMING ORGANIZATION REPORT NUMBER: NSMRL/F1705/TR--2021-1351

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Deep Submergence Biomedical Development
Commander Naval Sea Systems Command
1333 Isaac Hull Avenue, SE
Washington Navy Yard, DC 20376

10. SPONSOR/MONITOR'S ACRONYM(S): DSBD

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The present study aimed to conduct a DISSUB simulation that included a constellation of environmental, mental, and physical stressors in order to determine their effects on human cognitive and operational performance. Thirteen volunteers participated in a five-day disabled submarine (DISSUB) simulation in the Naval Submarine Medical Research Laboratory (NSMRL) hypo/hyperbaric chamber. Ten DISSUB-like stressors including thermal changes (temperature and humidity), atmospheric composition (oxygen and carbon dioxide), dim lighting, confinement/isolation, boredom, hygiene, nutrition, caffeine withdrawal, pain, and fatigue were imposed and/or measured during the simulation. Cognitive performance, operational performance, and mood were evaluated through daily assessments and questionnaires. While the study was successful in conducting a multi-day simulation with no participant attrition, safety and ethical concerns limited the ability to replicate a fully-realistic DISSUB scenario. No significant change in performance accuracy on the cognitive assessments or the operational measures was observed.

15. SUBJECT TERMS

DISSUB, disabled submarine, cognitive performance, operational performance, stress

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	SAR	38	NAVSUBMEDRSCHLAB Commanding Officer
					19b. TELEPHONE NUMBER *(Include area code)* 860-694-3263

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Acknowledgments

The authors would like to thank the following NSMRL staff for invaluable assistance with this project: ND1 Kyle Smith, ND1 Scott Gee, ND2 Brandon Young, HN Joshua Harris, and HN Todd Emerson for maintaining a 24-hour watchbill for the monitoring of study subjects; Mr. Lou Deflice and Mr. John Connors for assisting with all chamber operations; CDR Doug McAdams, LT Luke Beardslee, and LT Kyle Vaught for serving as Medical Monitors and providing participant medical screenings; Dr. Justin Handy for monitoring data collection activities in the absence of the Principal Investigator; and Dr. Paul Reinhart and Ms. Alexia Bohnenkamper for assistance with recruitment and data collection.

Abstract

The present study aimed to conduct a disabled submarine (DISSUB) partial simulation that included a constellation of environmental, mental, and physical stressors in order to determine their effects on human cognitive and operational performance. Thirteen volunteers participated in a five-day DISSUB simulation in the Naval Submarine Medical Research Laboratory (NSMRL) hypo/hyperbaric chamber, at 1 atmosphere. Ten factors that could be potential stressors in a DISSUB were imposed and/or measured during the simulation: thermal changes (temperature [72.2 – 80.3˚F] and humidity [52.3 – 85.5 %RH]), atmospheric composition (oxygen [20 – 21.5 % SEV] and carbon dioxide [888 – 7392 PPM]), dim lighting, confinement, isolation, boredom, sub-optimal hygiene, sub-optimal nutrition, caffeine withdrawal, pain, and fatigue. Cognitive performance, operational performance, and mood were evaluated through daily assessments and questionnaires. While the study was successful in conducting a multi-day partial simulation with no participant attrition, safety and ethical concerns limited the ability to replicate a fully realistic DISSUB scenario. Due to each of the conditions being present simultaneously, rather than manipulated in a controlled fashion, we were unable to elucidate any potential positive or negative effects of individual factors. No significant change in performance accuracy on the cognitive assessments or the operational measures was observed, but completion time for the operational measures significantly declined over the course of the simulation period, indicating a substantial practice effect. These findings, though not clearly elucidating the effects of DISSUB-like stressors on performance, have considerable implications for how submariners are trained and how future simulation-based research efforts can maximize their likelihood of success.

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List of Acronyms and Symbols

%	Percent
>	Greater than
<	Less than
°	Degrees
BART	Balloon Analogue Risk Task
BPS	Boredom Proneness Scale
CMDQ	Cornell Musculoskeletal Discomfort Questionnaire
CO_2	Carbon dioxide
CT	Connecticut
DANA	Defense Automated Neurobehavioral Assessment
DISSUB	Disabled submarine
EAB	Emergency air breather
e.g.	For example
F	Fahrenheit
fl	Fluid
FS	False start
ft	Feet
GNG	Go/no-go
i.e.	In other words
kcal	Kilocalories
kcal/day	Kilocalories per day
kcal/hr	Kilocalories per hour
kg	Kilograms
KSS	Karolinska Sleepiness Scale
LMM	Linear mixed-effects model
M	Mean
mg	Milligrams
mg/day	Milligrams per day
mins	Minutes
mm	Millimeter
ms	Milliseconds
MSBS	Multidimensional State Boredom Scale
NAVSEA	Naval Sea Systems Command
NSMRL	Naval Submarine Medical Research Laboratory
oz	Ounces
oz/hr	Ounces per hour
O_2	Oxygen
POMS	Profile of Mood States
ppm	Parts-per-million
PRT	Procedural reaction time
PVT	Psychomotor Vigilance Task

RH	Relative humidity
RT	Reaction time
SD	Standard deviation
SE	Standard error
SEAL	Submarine Escape Action Levels
SEV	Surface equivalent value
SLIM	Satiety Labeled Intensity Magnitude
SRT	Simple reaction time
SSN	Nuclear-powered attack submarine
TMD	Total mood disturbance
WCST	Wisconsin Card Sorting Task

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Introduction

Despite extensive advances in submarine engineering and technology, a submarine may become disabled underwater and be unable to resurface due to inciting events, such as systems failure, collision, explosion, fire, or flooding (Whybourn, Fothergill, Quatroche, & Moss, 2019). Historical records suggest that the majority of disabled submarine (DISSUB) events are survivable (Whybourn et al., 2019); however, submariners who survive the inciting event may become trapped in the DISSUB and endure life-threatening conditions, including increased temperature (Horn et al., 2009), extreme stress (Ochsner, 2003), and shortages of food or water (Harvey & Carson, 1989). While exposed to these stressors, survivors must perform cognitively-demanding tasks that affect their likelihood of survival, such as monitoring their surroundings, completing stay-time calculations, carrying out unfamiliar protocols, and mitigating emergency situations.

A review conducted by Chabal, Bohnenkamper, Reinhart, and Quatroche (2019) classified 34 stressors that have the potential to affect submariners in a DISSUB scenario, and categorized them as environmental, mental, or physical. Environmental stressors were defined as those that originate within the submarine, such as exposure to air pollutants, decreased oxygen (O_2) levels, and flooding (Harvey & Carson, 1989; McMillan, 1970; Mole, 1989). Mental stressors were defined as those that may induce feelings of tension, irritability, thoughts of worry, or any factors (e.g., confinement, feelings of hopelessness, and conflict among survivors) that may result in a state of anxiety (Gertner, Duplessis, & Horn, 2008; Mole, 1989). Physical stressors can stimulate a physical reaction of the body and included caffeine withdrawal, dehydration, fatigue, poor hygiene (due to insufficient water for cleaning or a buildup of sanitary waste), changes in nutrition (high fat diet, food rationing), and pain or injury (DeMers, Horn, & Hughes, 2009; Horn et al., 2009; Ochsner, 2003).

A second review by Chabal, Bohnenkamper, Moslener, and Casper (2020) found that much of what is known about the effects of the stressors present during a DISSUB event is physiological in nature, and minimal attention has been paid to the cognitive ramifications of these stressors. For example, the majority of DISSUB research has focused on developing technological advancements such as rescue vehicles or personal protective equipment to minimize the physiological effects of the DISSUB environment (e.g., Eckenhoff, 1984; Kargher, Ryder, Wray, Woolrich, & Horn, 2001; LaPenna, 2009). Few studies have examined how the stressors aboard a DISSUB are likely to affect human performance, particularly how conditions can interfere with the survivors' ability to successfully perform the cognitively-demanding tasks that are necessary for survival.

In some cases, only a handful of studies have explored the cognitive impact of a particular stressor that may occur in a DISSUB environment (e.g., effects of degraded hygiene). For many stressors, conflicting findings are common as a consequence of variability in participant selection, task parameters, operational definitions, and data analysis techniques across studies. For example, elevated ambient levels of carbon dioxide (CO_2) may degrade decision making in an office environment (Satish et al., 2012), but similar effects have not been observed in a submarine environment (Rodeheffer, Chabal, Clarke, & Fothergill, 2018). Moreover, rarely have stressors been investigated under conditions representative of a DISSUB scenario where survivors are subjected to constant or near-constant stressor exposure for up to seven days. For example, the effects of caffeine withdrawal have primarily been assessed 24-48 hours following caffeine cessation (Couturier, Laman, van Duijn, & van Duijn, 1997; Silverman, Evans, Strain,

& Griffiths, 1992); however, during a DISSUB scenario individuals may be without access to caffeine sources and withdrawal could continue for three to seven days. Lastly, stressors have typically been investigated in isolation, which is not representative of a DISSUB scenario in which survivors will be exposed to a constellation of factors that could interact to produce different effects on human performance and cognition.

The purpose of this study was to understand how environmental, mental, and physical stressors likely present during a DISSUB scenario may interact with and affect human cognition. A laboratory-based, simulated DISSUB environment was designed to simultaneously introduce specific DISSUB-like stressors over a continuous five-day period. Induced stressors were limited to those that could be safely and ethically manipulated (e.g., participants could not be exposed to toxic gases; pressure could not be manipulated due to chamber certification limitations at the time of the study). Cognitive performance, operational performance, and mood were tracked throughout the duration of the stressor exposure in order to understand how a DISSUB-like environment may impact survivors' ability to perform given continued exposure to a DISSUB environment.

Methods

Statistical Design

This study utilized a within-subjects, repeated-measures design containing multiple assessment periods conducted routinely throughout the duration of a five-day[1] experimental simulation. Participants completed the simulation in cohorts that ranged from 2-3 subjects in the Naval Submarine Medical Research Laboratory (NSMRL) hypo/hyperbaric chamber (23 ft long and 9 ft diameter from the back wall to the outer lock) in Groton, CT.

Participants

Fifteen volunteers were recruited to participate in the study through flyers, online advertising, and word of mouth. All participants completed an informed consent process approved by the NSMRL local Institutional Review Board (NSMRL.2019.0004). Only healthy, non-nicotine users with no history of metabolic disorder (e.g., diabetes), endocrine disorder, cardiovascular disorder, cancer, kidney disease, lung disease, anemia, epilepsy/seizures, claustrophobia, panic attacks, or sleepwalking were included in the study. Two participants were excluded from participation during baseline testing because they did not meet one of the inclusion criteria. The remaining 13 participants were males between the ages of 19 and 37 years, with a mean age of 24.6 years (*SD* = 5.8 years). While females were not specifically excluded from the study, there were not enough female volunteers to conduct a full trial, as each trial was required to be gender-matched (i.e., each trial must have been either all males or all females). Seven participants were current active-duty military members and six were civilians.

Demographic and Trait-like Measures

Boredom Proneness Scale (BPS). The BPS is a 28-item self-report questionnaire that measures the tendency to experience boredom (Farmer & Sundberg, 1986). Responses are rated on a 7-point ("Strongly Disagree" to "Strongly Agree") Likert scale, where high scores indicate a

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[1] Participants completed the study around 1:30 PM on the fifth day of the simulation. For descriptive purposes we still refer to the study as a five-day simulation even though the final day was shorter than the first four days.

greater tendency to experience boredom compared to lower scores. Item examples include, "I don't feel motivated by most things that I do."

Caffeine Use Questionnaire. The Caffeine Use Questionnaire is a self-report questionnaire that measures use of 30 caffeinated products over the past month. The average caffeine consumption is calculated in mg/day based on the amount and frequency of consumption of each caffeinated product (Knapik et al., 2016).

Eysenck Impulsiveness Questionnaire. The Eysenck Impulsiveness Questionnaire is a 54-item questionnaire consisting of a series of yes-no questions such as "Do you generally do and say things without stopping to think?" The results of the questionnaire provided a score for impulsiveness (tendency to act with limited forethought), venturesomeness (proclivity for venture seeking behavior), and empathy (ability to understand and relate to others' feelings) personality traits (Eysenck, Pearson, Easting, & Allsopp, 1985).

Caloric Intake

Home Food Diary. Participants completed a record of daily food consumption every day for the three days leading up to the simulation. Each entry included a detailed description of all foods and beverages (except for water) consumed and the date and time of consumption. Each participant's daily caloric intake was calculated by the research team.[2]

Cognitive and Mood Assessments

Defense Automated Neurobehavioral Assessment (DANA). The 5-minute version of the DANA was used to assess simple reaction time (SRT), procedural reaction time (PRT), and performance on a go/no-go task (Lathan, Spira, Bleiberg, Vice, & Tsao, 2013).

Psychomotor Vigilance Task (PVT). Sustained attention/vigilance was measured using a 20-minute version of the PVT (Dinges & Powell, 1985). Visual stimuli were presented at a variable inter-stimulus-interval (2-10 seconds), and remained on the screen until participants responded by left-clicking a mouse as quickly as possible. The stimulus was a "timer" that displayed the number of milliseconds since stimulus onset until it was stopped by the response, briefly displaying the reaction time for that trial. The final score was recorded as average reaction time.

Delayed Memory Recall. Memory capacity was measured using a delayed recall task. The stimuli used in this task were 100 abstract and concrete two-syllable nouns (e.g., *candy*, *actor*, *towel*, etc.) of similar lexical frequency (Brysbaert & New, 2009). For each testing session, ten nouns were randomly selected without replacement and presented verbally with an approximate one second interval between words. After 30 minutes, participants were given 120 seconds to record as many words as they could using a pen and paper. The final score was recorded as the number of words recalled correctly.

Digit Span. Working memory capacity was measured using a 21-set digit span task. Participants were verbally presented with progressively longer sequences of numbers (2-8 digits per set) and were required to record the digit set in the correct order immediately following presentation. The final score was recorded as the number of digit sets that the participant completed correctly until three sets in a row were missed.

Wisconsin Card Sorting Task (WCST). Flexible thinking was assessed using the 64-item WCST (Grant & Berg, 1948). The WCST consisted of key cards and response cards with

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[2] As participants were not provided fixed meals, caloric intake for the days leading up to the simulation may be over- or under-estimated.

varying geometric figures. Participants were required to correctly classify response cards in relation to key cards by following implicit rules. The final score was recorded as percent correct, broken down into total errors, perseverative errors, and non-perseverative errors.

Balloon Analogue Risk Task (BART). Risk-taking propensity was measured using the BART (Lejuez et al., 2002). The BART consisted of 90 "balloons" that participants inflated using mouse clicks in order to accrue points. With each pump of the balloon, points were accumulated in a temporary bank; however, if the balloon was inflated past its explosion point it popped, losing any accumulated points. Participants had to transfer the funds from the temporary bank to a permanent bank prior to balloon explosion in order to accrue the points. The final score was recorded as the adjusted mean number of pumps on unexploded balloons.

Profile of Mood States (POMS). The 40-item Abbreviated POMS was used to assess mood (Grove & Prapavessis, 1992). Participants used a 5-point Likert scale ("Not at all" to "Extremely") to rate how different words describe their current feelings (e.g., "Tense"). Participants' total mood disturbance (TMD) was computed using the individual scores from six different mood dimensions (vigor-activity, fatigue-inertia, depression-dejection, confusion-bewilderment, tension-anxiety, and anger-hostility).

Operational Measures

As operational measures, participants completed calculations that are included in the SSN 774 Class Disabled Submarine Survival Guide (also referred to as the Guard Book) (NAVSEA, 2013). The Guard Book is located in each compartment on every submarine and it contains all the necessary steps and procedures for how to survive, escape, and be rescued from a DISSUB.

Management of toxic gases. Participants were provided hypothetical concentrations of toxic gases that could be present during a DISSUB event. Values provided were counterbalanced across days. Participants were asked to follow the Guard Book instructions to complete calculations for the management of these gases, and determine whether Emergency Air Breather masks (EABs) would be required. Participants were given a standard handheld calculator, paper, and a pen to complete this task. The primary outcome measure was whether participants arrived at the correct conclusion according to the Guard Book (i.e., did they recommend the use of EABs appropriately based on the gas levels). A secondary outcome measure was the amount of time that it took participants to perform the calculations and reach a conclusion about EAB use. The time was recorded by the research team using a handheld stopwatch.

Carbon dioxide and oxygen stay-time calculations. Participants used instructions in the Guard Book to calculate "stay-time", or the amount of time available to wait for rescue before attempting to escape from a submarine. To complete the calculations, participants were provided with hypothetical values for variables including carbon dioxide (CO_2) levels, oxygen (O_2) levels and number of fit and unfit survivors, which were counterbalanced across days. Participants used a standard handheld calculator, paper, and a pen to complete this task. The primary outcome measure was whether participants correctly calculated the stay-times. A secondary outcome measure was the amount of the time it took participants to perform the calculations. Completion time was measured by the research team using a handheld stopwatch.

Questionnaire Battery

Evaluation of the chamber environment. This series of 7-point Likert scales asked participants to rate the current quality of the chamber environment with respect to temperature ("much too cool" to "much too warm"), freshness of air quality ("very dissatisfied" to "very satisfied"), and odor ("very dissatisfied" to "very satisfied"; Rodeheffer et al., 2018).

Claustrophobia Scale. The 20-item Claustrophobia Scale (Öst, 2007) was used to assess claustrophobia across two subscales: one for measuring anxiety over a hypothetical scenario and one for avoidance of hypothetical scenarios (e.g., "standing in such a crowd that you cannot move at all"). Participants rated their anxiety on a 5-point Likert scale ("none" to "very much") and their avoidance on a 3-point Likert scale ("would not avoid" to "would always avoid").

Multidimensional State Boredom Scale (MSBS). The 29-item MSBS (Fahlman, Mercer-Lynn, Flora, & Eastwood, 2013) was used to assess participant boredom. Participants used a 7-point Likert scale ("strongly disagree" to "strongly agree") in response to a variety of statements related to boredom (e.g., "time is passing by slower than usual"). A composite boredom score was computed for each subject using the individual scores from five subscales.

Satiety Labeled Intensity Magnitude (SLIM). The normed and validated SLIM (Cardello, Schutz, Lesher, & Merril, 2005) scale was used to measure participant hunger on a visual analogue scale with endpoints of -100 representing "greatest imaginable hunger" and 100 representing "greatest imaginable fullness."

Headache questionnaire. A headache questionnaire was used to measure the prevalence and severity of any headaches experienced by participants. Participants indicated whether they were experiencing a headache at the time they were filling out the questionnaire. If so, they rated the intensity of the headache on a 100 mm visual analogue scale containing endpoints from "no pain" to "most severe pain imaginable" (Loder & Burch, 2012). Participants also described the pain of their headache using a list of provided words such as "throbbing" or "sharp."

Karolinska Sleepiness Scale (KSS). The KSS (Akerstedt & Gillberg, 1990) was used to measure subjective sleepiness. Subjects indicated their current wakefulness on one 10-point Likert scale from "Extremely alert" to "Extremely sleepy, can't keep awake."

Cornell Musculoskeletal Discomfort Questionnaire (CMDQ). The CMDQ (Hedge, 1999) measured pain prevalence and intensity in specific body parts. Participants indicated whether they were experiencing any pain in specific body parts (e.g., "left lower leg") and the magnitude of pain experienced ("slightly uncomfortable," "moderately uncomfortable," or "very uncomfortable"). The CMDQ was modified from its original format to inquire about the experience of pain in the moment, rather than over the past week.

Thirst rating scale. This 4-point Likert scale asked participants to rate their current thirst levels ("very thirsty," "moderately thirsty," "slightly thirsty," or "not at all thirsty").

Procedure

Baseline. Prior to the five-day simulation, participants completed two to three baseline sessions to become familiar with all testing procedures. While every effort was made to have all participants complete three full baseline sessions, scheduling conflicts prevented four participants from completing the third session. During the first baseline session, participants completed the demographic and trait-like questionnaires, practiced the daily questionnaire battery, and practiced the cognitive assessment test and operational measures calculations. During the second and third baseline visits, participants practiced the cognitive assessment tests and operational measures calculations. All questionnaires, tests, and calculations were completed within NSMRL's hypo/hyperbaric chamber so that participants became accustomed to the setting.

Baseline dietary intake data were captured through participant completion of a comprehensive food diary for the three days leading up to the DISSUB simulation period. Participants were instructed to abstain from alcohol consumption during the three-day period prior to the start of the simulation.

DISSUB Simulation. For the duration of the study, participants were under continuous investigator supervision through the use of three video cameras inside the chamber to ensure participant safety as well as to ensure study compliance and standardization of all study-related activities. Several variables, each constituting a potential stressor aboard a DISSUB, were measured or actively imposed:

Potential environmental stressors:

1. Thermal. Temperature and humidity within the chamber were permitted to fluctuate freely. Values for both temperature and humidity were recorded every 30 minutes for both the inner and outer lock of the chamber, and the temperature was not to exceed 85°F. If the temperature began to rise to unsafe levels, the medlock hatch on the side of the chamber was opened for additional air ventilation. The medlock hatch was opened approximately 2 to 4 inches for the entire duration of the study, but was only fully opened when ventilation was necessary. Additionally, the hatches for both the inner and outer locks of the chamber were fully opened for the duration of the study to allow for ventilation, though the outer lock door was covered with thick, dark fabric.
2. Atmospheric composition. Atmospheric levels (CO_2 and O_2) were permitted to fluctuate freely. Levels were recorded every 30 minutes for the inner and outer lock of the chamber and were not to reach levels of ≥ 9,999 ppm CO_2 or ≤ 16% SEV O_2. If the environmental conditions began to approach the above limits, the medlock hatch on the side of the chamber was opened fully for additional air ventilation.
3. Lighting. To mimic the lighting conditions of a DISSUB scenario, light-blocking fabric was used to cover the chamber entrance and windows, and lighting within the chamber was limited to two portable lantern floodlights for participants to use at their discretion. Lanterns were similar to what would be found aboard a submarine, though were likely slightly different from those employed during a DISSUB scenario (Horn et al., 2009). Due to each battle lantern having had an estimated battery life of seven hours, each night a researcher exchanged the used battle lanterns from the previous day with fully-charged lanterns. Participants were also issued a handheld flashlight for personal use. In the event that a participant needed to exit the chamber (i.e., to use the restroom), overhead lights in the hallway and restroom were turned off prior to the participant exiting the chamber, windows in the hallway were covered with cardboard to block daytime light, and participants wore blue-light blocking glasses.

Mental stressors:

1. Confinement and isolation. For the duration of the simulation, subjects were confined to the 23 ft long x 9 ft diameter hypo/hyperbaric chamber. While both the inner and outer lock hatches were left completely open to allow for air ventilation, the entry to the chamber was fitted with a light-blocking curtain to maintain the appearance of being sealed shut. Within the chamber, three mattress racks were fitted with sheets, a blanket, and a pillow for sleeping. All necessary interactions between research personnel and the participants occurred using the chamber’s two-way intercom. Participants were permitted

to leave the chamber only to use the restroom, and all excursions were carefully logged by research personnel. There was no limit to the number of excursions a participant could take or the duration of each excursion. Participants did not have access to any devices with external communication capabilities (e.g., cell phones, WiFi-enabled devices, etc.).

2. Boredom. All activity was limited to the confined space of the chamber. Physically-demanding activities such as body weight exercise were discouraged, in order to mimic the procedures put in place to limit CO_2 production during a DISSUB (NAVSEA, 2013). Participants were permitted to bring a small duffle bag with items such as books, decks of cards, or charged devices that had been disconnected from the internet, as similar items would likely be available to crew members in a DISSUB scenario. Charging packs and electrical outlets were not provided.

Physical stressors:

1. Sub-optimal Hygiene. Participants were confined within the chamber for the entirety of the five-day simulation period except for use of a standard restroom outside the chamber where they had access to a toilet, a sink, and soap for handwashing. Showers were not permitted, and volunteers did not have access to any laundry facilities, but participants were permitted to change clothes if they chose to bring extra clothing items.
2. Sub-optimal Nutrition. During the simulation, participants adhered to a low-calorie/high-fat diet recommended by the DISSUB Guard Book (NAVSEA, 2013). Meals were provided twice a day and totaled approximately 1,300 kcal/day, similar to previous experimental DISSUB research (Risberg et al., 2004). Meals were composed of approximately 71% calories from fat, 13% calories from carbohydrates, and 17% calories from protein. The contents of each meal varied, but all meals contained items on the list of high fat foods from the food load out plan that is provided in the DISSUB Guard Book. Examples of foods provided include various cheeses, hot dogs, ham, mayonnaise, and honey roasted peanuts. Participants were not required to consume all of the provided food; any food not consumed was weighed and recorded. Water was provided *ad libitum* in the form of 16.9 fl. oz. bottles; daily water intake was measured by counting the number of water bottles consumed by each participant. Participants' body weight was recorded twice a day. Nutritional intervention was required for one participant, as the medical monitor was concerned about insufficient water intake; the participant was instructed to drink more water.
3. Caffeine withdrawal. Throughout the five-day simulation, participants were not permitted to consume caffeine in any form. While caffeine tablets may be available to crew members experiencing withdrawal symptoms during a DISSUB scenario (NAVSEA, 2013), availability is not always guaranteed. If a participant was a habitual caffeine user prior to the simulation period, the lack of caffeine during the simulation may have led to caffeine withdrawal symptoms.
4. Pain. While pain was never intentionally inflicted upon participants, there was the potential for individuals to experience musculoskeletal pain due to the limited ability for movement within the chamber and/or the unfamiliar sleeping conditions. Caffeine withdrawal may have led to headache symptoms.
5. Fatigue. While participants had ample time to rest during the simulation period, it is possible that the stress of the unfamiliar environment, the fluctuating atmospheric conditions, and the restricted movement while in the chamber caused insufficient sleep

and fatigue (Chabal et al., 2019). During the simulation, participants were not kept on a sleep schedule, but had to be awake prior to all study-related activities. If it appeared that a participant was sleeping, a warning was given over the intercom ten minutes prior to the start of the activity so that the participants would wake up.

All questionnaires and tests were completed at the same times each day to avoid time-of-day effects. The questionnaire battery and operational measures were administered using pen and paper, and the cognitive assessments were administered on laptop computers, handheld tablet devices, or with pen and paper. All computer and tablet based assessments were completed with the devices set to the lowest screen lighting level to limit extrinsic exposure to blue light. A researcher remained in the chamber during all cognitive and operational assessments to present stimuli, monitor participants, and record completion times. Daily questionnaires and meals were passed to participants through the chamber's medlock to minimize interactions with experimenters. See Table 1 for a comprehensive daily schedule. When participants were not engaged in study-related activities, they were encouraged to rest. This matches what would occur in a true DISSUB scenario, in which crew members are instructed to limit physical activity in order to minimize CO_2 production (NAVSEA, 2013). Upon completion of the simulation, participants were cleared by the study medical monitor before being permitted to depart the lab.

Time	Daily Schedule
0000-0700	Rest
0800	Arrive to lab (Day 1); rest (Days 2-5)
0900	Body weight measured
1000	Questionnaire battery
1100	Meal #1 served; SLIM scale*
1200	Behavioral test battery**
1300	Behavioral test battery** (continued)
1400	Rest; depart lab (Day 5)
1500	Rest
1600	Rest
1700	Rest
1800	Meal #2 served; SLIM scale*
1900	Questionnaire battery
2000	Rest
2100	Body weight and water intake measured; switch-out battle lanterns
2200-0000	Rest
*The SLIM scale was administered immediately prior to meal delivery and immediately following meal consumption. ** The Behavioral Test Battery included all cognitive assessments and operational measures.	

Table 1. Daily schedule for the five-day DISSUB simulation period.

Data Analysis

Statistical analyses were performed using R software (v. 3.6.2). Data were analyzed using linear mixed-effects models (LMM) for within-subjects data, and *p*-values were obtained from the "lmerTest" package in R (Kuznetsova, Brockhoff, & Christensen, 2017). For each LMM, day/time of testing was treated as the within-subjects variable and dependent measures were the performance on cognitive, questionnaire, and operational outcomes across the testing days and time. If statistical significance was found ($p < 0.05$), post hoc pair-wise t-tests with Holm-Bonferroni adjustments were performed. For categorical and ordinal data, Friedman's test for non-parametric data and pair-wise Wilcoxon Rank Sum Tests were used instead, respectively.

Results

Demographic and Trait-like Measures

Prior to initiation of the study, participants completed the Boredom Proneness Scale (M = 88.69, SD = 12.92), provided an estimate of their Caffeine Use (M = 113.03 mg/day, SD = 168.70 mg/day), and completed the Eysenck Impulsiveness Questionnaire (venturesome: M = 0.74, SD = 0.16; empathy: M = 0.55, SD = 0.23; impulsiveness: M = 0.32, SD = 0.17). The average score for the Boredom Proneness Scale was within the normal range of 81-117 for adults (higher scores indicating more proneness to boredom; Vodanovich & Kass, 1990) and the average amount of caffeine consumed by participants was lower than the average amount of caffeine consumed by the general population in the United States (M = 186 mg/day, SD = 4; Fulgoni, Keast, & Lieberman, 2015).

Evaluation of potential DISSUB-like Stressors

Potential environmental, mental, and physical stressors within the chamber were monitored throughout the stimulation. Changes in performance and mood over time were also measured.

Environmental stressors. Due to imposed safety precautions (i.e., ventilation through the medlock hatch if environmental conditions began to approach predefined limits set forth in the IRB protocol), environmental conditions did not directly simulate a true disabled submarine scenario.

Thermal. Temperature (M = 77.33 °F, SD = 1.36), and humidity (M = 64.76% RH, SD = 5.74) stayed within acceptable and safe levels throughout the duration of the study (see Figure 2). Average daily levels changed for both temperature ($\chi^2(4) = 151.15$, $p < 0.001$) and humidity ($\chi^2(4) = 148.80$, $p < 0.001$) throughout the simulation. Post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed a significant increase in temperature from Day 1 (M = 75.27 °F, SD = 0.78) when compared to Days 2-5 (all p's < 0.001), and a significant decrease in humidity each day of the simulation (all p's < 0.01) with the exception of Day 3 to Day 4 (p = 0.18) and Day 4 to Day 5 (p = 0.18). Neither temperature nor humidity were consistent with what would be expected during a DISSUB scenario. Temperature and humidity are expected to rise during a DISSUB event, with temperatures potentially reaching 80°F or above and humidity reaching levels of 90% RH in some areas of the submarine (Horn et al., 2009); this is contrary to the conditions of the present study.

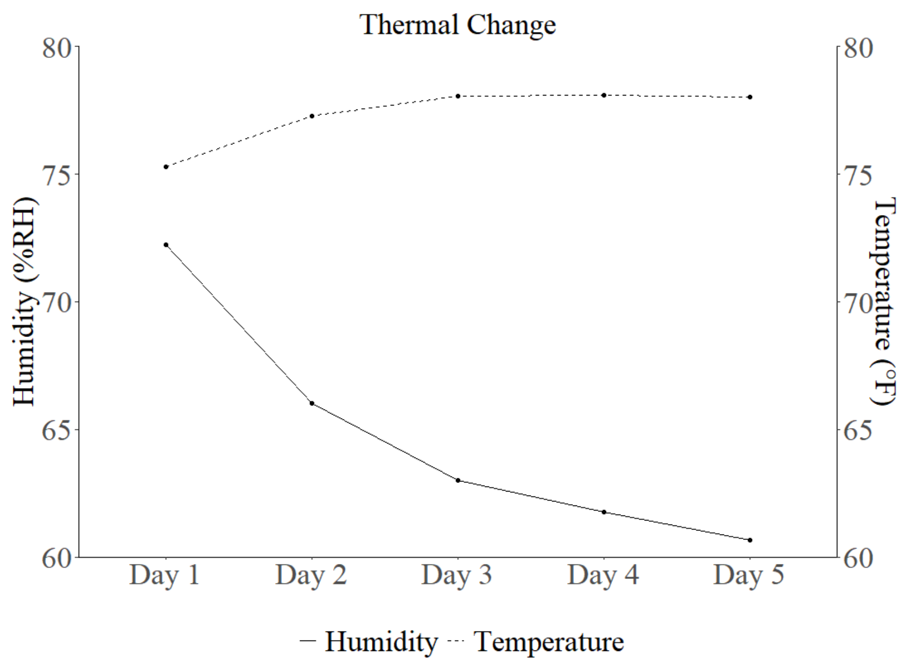

Figure 2. Thermal change. Average daily humidity and temperature levels on each day of the DISSUB simulation.

Atmospheric composition. Although daily levels varied for both CO_2 (M = 2,118.76 ppm, SD = 844.31; $\chi^2(4) = 179.89$, $p < 0.001$) and O_2 (M = 20.80% SEV, SD = 0.27; $\chi^2(4) = 220.20$, $p < 0.001$), concentrations stayed within acceptable and safe levels throughout the duration of the simulation (see Table 1). Post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed a significant decrease in CO_2 levels each day of the simulation (all p's < 0.05) with the exception of Day 3 to Day 4 ($p = 0.25$) and Day 4 to Day 5 ($p = 0.06$) when CO_2 levels remained fairly consistent. Additionally, O_2 levels steadily and significantly increased each day of the simulation (all p's < 0.01) with the exception of Day 3 to Day 4 ($p = 0.44$). This change in atmospheric composition is not what would be expected during a true DISSUB scenario where CO_2 levels are expected to rise and, with the use of countermeasures, be maintained between 1.5% - 2.5% SEV (15,000-25,000 ppm at sea level), and O_2 levels are expected to fall to around 17% SEV (Chabal et al., 2019; Horn et al., 2009; NAVSEA, 2013). The levels observed in the present study are within the 90 day submarine atmosphere limit for normal submarine operations, and therefore would not be considered a stressor to participants.

Table 1
Average daily CO_2 and O_2 levels

Measure	Day 1	Day 2	Day 3	Day 4	Day 5	*P* Statistic
CO_2 (PPM)	3545.52 (794.77)	2121.02 (235.77)	1738.12 (249.97)	1668.89 (252.52)	1520.25 (148.12)	<0.001
O_2 (%SEV)	20.55 (0.26)	20.80 (0.24)	20.87 (0.25)	20.88 (0.25)	20.91 (0.24)	<0.001

Note. Values represent means. Those in parentheses represent standard deviations.

Subjective evaluation of the chamber environment. See Table 2 for a summary of participant ratings on the chamber environment.

Table 2
Evaluation of environmental stressors

Measure	Day 1	Day 2	Day 3	Day 4	Day 5	*P* Statistic
Eval. of Chamb. (Freshness)	4.26 (0.81)	4.04* (0.66)	3.92 (0.57)	3.77 (0.93)	3.54 (0.66)	<0.01
Eval. of Chamb. (Odor)	4.19 (0.75)	4.07* (0.64)	3.88 (0.65)	3.73 (1.05)	3.38 (0.87)	<0.01
Eval. of Chamb. (Temperature)	4.07 (0.79)	4.38* (0.89)	4.54 (0.92)	4.58 (0.86)	4.31 (1.25)	0.07

Note. Values represent means. Those in parentheses represent standard deviations.
*Missing data ($N = 12$)

Mental stressors. The experimental design created the possibility for emergence of feelings of confinement/isolation and boredom. While physical confinement and isolation was achieved, this did not result in subjective feelings of claustrophobia or boredom.

Confinement/isolation. Despite the considerable amount of time that participants spent isolated within the enclosed chamber, participants did not report any increases in feelings of claustrophobia throughout the duration of the simulation (indicated by a failure to detect change in the Claustrophobia Scale ratings throughout the five-day simulation period; all *p*'s > 0.05; see Table 3). Participants left the simulated disabled submarine environment to use the restroom facilities anywhere from 12 to 48 times during the course of the five-day study ($M = 25.77$ excursions per participant, $SD = 9.75$). The average duration per excursion was 4.18 minutes ($SD = 1.20$). The number of excursions per day changed significantly throughout the course of the simulation ($\chi^2(1, N = 13) = 4.13$, $p < 0.05$). Post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed a significant increase in the number of excursions per day from Day 1 ($M = 4.15$, $SD = 1.82$) to Day 2 ($M = 6.85$, $SD = 1.91$; $p < 0.01$), and a significant decrease in the number of excursions from Day 2 ($M = 6.85$, $SD = 1.91$), Day 3 ($M = 6.15$, $SD = 2.88$), and Day 4 ($M = 6.15$, $SD = 3.18$) to Day 5 ($M = 2.54$, $SD = 1.45$; $p < 0.001$). These significant effects are likely due to the fact that Days 1 and 5 were shorter in length than Days 2-4 (i.e., participants arrived at 8:00 AM on Day 1 and departed at 1:30 PM on Day 5).

Boredom. There was no significant change detected in participants' ratings on the Multidimensional State Boredom Scale (MSBS) throughout the five-day simulation period ($\chi^2(8, N = 13) = 5.41$, $p = 0.71$; see Table 3).

Table 3
Evaluation of mental stressors

Measure	Day 1		Day 2		Day 3		Day 4		Day 5	*P* Statistic
	1000	1900	1000	1900	1000	1900	1000	1900	1000	
Claustrophobia (Anxious)	0.38* (0.26)	0.33 (0.26)	0.34 (0.29)	0.28* (0.23)	0.33 (0.27)	0.35 (0.25)	0.33 (0.20)	0.31 (0.22)	0.32 (0.22)	0.88
Claustrophobia (Avoid)	0.21* (0.13)	0.18 (0.15)	0.19 (0.15)	0.17* (0.16)	0.19 (0.15)	0.21 (0.16)	0.20 (0.17)	0.19 (0.13)	0.23 (0.16)	0.24
MSBS (Total)	74.0* (6.9)	72.7 (7.2)	70.7 (5.9)	78.2 (7.2)	72.4 (6.5)	71.9 (6.4)	76.2 (5.6)	75.4 (6.3)	71.1 (5.3)	0.71

Note. Values represent means. Those in parentheses represent standard deviations.
*Missing data (*N* = 12)

Physical stressors. The metrics used to assess the presence of physical stressors are summarized in Table 4. Evidence was observed for potentially stressful nutritional changes (including diet, satiety, and caffeine withdrawal) but not for pain and fatigue.

Table 4
Evaluation of physical stressors

Measure	Day 1		Day 2		Day 3		Day 4		Day 5	*P* Statistic
	1000	1900	1000	1900	1000	1900	1000	1900	1000	
SLIM (Pre)	-6.9 (27.1)	-20.6 (17.8)	-23.4 (18.1)	-25.2 (23.2)	-27.4 (25.7)	-27.3 (28.7)	-30.4 (23.0)	-21.1 (34.0)	-29.5 (29.2)	0.32
SLIM (Post)	39.5 (16.7)	25.0 (25.1)	32.1 (25.5)	15.7 (24.8)	7.1 (26.9)	21.5 (29.6)	11.6 (24.7)	19.1 (27.9)	27.1 (32.6)	<0.01
Thirst	0.4 (0.5)	0.2* (0.4)	0.6 (0.7)	0.3* (0.5)	0.3 (0.5)	0.3 (0.5)	0.3 (0.5)	0.2 (0.4)	0.4 (0.5)	0.26
CMDQ	0.2 (0.4)	0.2 (0.4)	0.6 (0.9)	0.4* (0.8)	0.5 (0.8)	0.3 (0.8)	0.4 (0.8)	0.2 (0.4)	0.4 (0.8)	0.17
Headache	0.0 (0.0)	0.0 (0.0)	0.1 (0.3)	0.3 (0.5)	0.1* (0.3)	0.0 (0.0)	0.1 (0.3)	0.0 (0.0)	0.0 (0.0)	<0.05
KSS	3.9 (1.7)	4.3* (1.5)	4.2 (1.3)	4.8* (1.1)	4.6 (1.8)	4.1 (1.3)	4.2 (1.3)	3.8 (1.3)	3.8 (1.4)	0.24

Note. Values represent means. Those in parentheses represent standard deviations.
*Missing data (*N* = 12)

Nutrition. A DISSUB-like diet was successfully implemented during the simulation. To account for the varying number of hours spent in the chamber on Days 1 and 5 of the simulation, caloric intake per hour was calculated by dividing the amount of calories consumed by the number of hours spent in the chamber that day. For the three days leading up to the simulation, caloric intake was divided by 24 hours. Participants reported consuming an average of 79.92 kcal/hr (SD = 20.91) each of the three days prior to the simulation, and consumed an average of 51.51 kcal/hour (SD = 6.74) each day of the simulation ($t(12) = 5.55$, $p < 0.001$, $d = 2.17$). See Table 5 for a summary of daily caloric intake.

Throughout the simulation, caloric intake per hour varied significantly ($\chi^2(4, N=13) = 188.03$, $p < 0.001$). Post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed that participants consumed more calories per hour on Day 1 (*M* = 73.97 kcal/hr, *SD* = 9.22) when compared to all other days (all *p*'s < 0.001). Additionally, participants consumed more calories per hour on Day 3 (*M* = 53.64 kcal/hour, *SD* = 4.71) when compared to Day 2 (*M* = 44.71 kcal/hr, *SD* = 6.11, $p < 0.01$), Day 4 (*M* = 45.15 kcal/hr, *SD* = 10.07, $p < 0.05$), and Day 5 (*M* = 40.21 kcal/hr, *SD* = 13.48, $p < 0.01$).

Table 5
Caloric intake

Day	*Mean (SD) kcal*
-3	2080 (711)
-2	1949 (593)
-1	1754 (522)
1	1184 (148)
2	1073 (147)
3	1287 (113)
4	1084 (242)
5	522 (175)*

Note. Days -3, -2, and -1 occurred during baseline; Days 1-5 occurred during the simulation.
*Caloric intake is lower on Day 5 due to a fewer number of hours spent in the chamber that day.

Post-meal SLIM scale values changed over time ($\chi^2(8, N = 13) = 28.36$, $p < 0.01$), and post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed a decrease in satiety from the first meal on Day 1 (*M* = 39.46, *SD* = 16.65) when compared to the first meal on Day 4 (*M* = 11.62, *SD* = 24.67; $p < 0.001$). Pre-meal SLIM scale values did not change over time (see Table 4).

To account for the varying number of hours spent in the chamber on Days 1 and 5, water consumption per hour was calculated by dividing the amount of water consumed in a day by the number of hours spent in the chamber that day. On average, participants drank 3.17 oz/hr (*SD* = 1.22), 2.87 oz/hr (*SD* = 1.33), 2.93 oz/hr (*SD* = 1.43), 3.07 oz/hr (*SD* = 1.43), and 2.03 oz/hr (*SD* = 1.28) of water on Days 1 - 5 of the study, respectively. While initial analyses suggested a change in water consumption throughout the simulation ($\chi^2(1, N = 13) = 6.42$, $p < 0.05$), post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed that this significance was driven by a difference in water consumption between Day 3 and Day 5 ($p < 0.05$), with no difference in water consumption between the other days (all *p*'s > 0.10). Thirst ratings did not significantly change throughout the simulation ($\chi^2(8, N = 13) = 15.33$, $p = 0.06$).

Participants lost 3.42% (*SD* = 0.45) of their body weight, or 0.70 kg (*SD* = 3.00), from beginning to end of the study ($t(12) = 16.31$, $p < 0.001$, $d = 6.40$). The weight loss that participants experienced, combined with the reduction in calories consumed during the simulation, confirms that potentially stressful changes in nutrition were successfully imposed.

Caffeine withdrawal. Participants reported consuming an average of 113.03 mg (*SD* = 168.70) of caffeine per day prior to the start of the simulation. Two participants consumed no caffeine during the month prior to the simulation, seven participants consumed low amounts of caffeine (1 - 100 mg/day), two participants consumed moderate amounts of caffeine (101 - 400 mg/day), and two participants consumed high amounts of caffeine (> 400 mg/day; McLellan, Claldwell, & Lieberman, 2016). Withdrawal symptoms are known to occur within approximately three days in users of 100 mg/day or more of caffeine (Evans & Griffiths, 1999); therefore it is likely that the participants who consumed moderate or high amounts of caffeine experienced withdrawal symptoms.

Pain. There was no significant change detected in participant ratings on the Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) throughout the five-day simulation period ($\chi^2(8, N = 13) = 11.62, p = 0.17$). Although initial analyses suggested a change in the number of headaches experienced per day ($\chi^2(8, N = 13) = 18.07, p < 0.05$), post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed no significant differences across days (all *p'*s > 0.10). Forty percent (6 of total 15 participants) of participants reported headaches during the simulation, with severities ranging from 4 to 30 (mean 7.38).

Fatigue. There was no significant change detected in participant ratings on the Karolinska Sleepiness Scale (KSS) over the course of the simulation ($\chi^2(8, N = 13) = 10.35, p = 0.24$).

Evaluation of Mood and Cognitive Performance

There was no significant change detected in Total Mood Disturbance (TMD) scores on the Profile of Mood States (POMS) over the course of the simulation ($M = -10.74$, $SD = 15.75$, $\chi^2(8, N = 13) = 9.90, p = 0.27$). Cognitive performance over the duration of the simulation is summarized in Table 6. As shown, no significant changes occurred over time for any task (all *p'*s > 0.05).

Table 6
Performance on cognitive assessments

Measure	Day 1	Day 2	Day 3	Day 4	Day 5	*P* Statistic
DANA (SRT)	180.7 (27.5)	191.1 (22.9)	189.3 (20.8)	179.7 (25.7)	189.0 (26.6)	0.10
DANA (SRT % Correct)	96.9 (6.8)	98.8 (1.9)	99.4 (1.5)	98.5 (1.9)	98.5 (2.6)	0.35
DANA (PRT)	103.6 (17.8)	109.7 (10.1)	111.2 (11.1)	108.9 (10.6)	109.5 (15.0)	0.29
DANA (PRT % Correct)	96.2 (4.1)	96.9 (4.2)	95.9 (3.7)	97.4 (3.1)	96.2 (2.2)	0.77
DANA (GNG)	126.4 (17.2)	129.1 (13.4)	133.4 (12.1)	129.2 (13.7)	131.4 (12.2)	0.21
DANA (GNG % Correct)	97.7 (3.7)	98.7 (1.7)	98.0 (2.1)	98.0 (2.6)	96.4 (2.5)	0.21
WCST (Total Error)	0.20 (0.06)	0.21 (0.06)	0.20 (0.07)	0.21 (0.05)	0.17 (0.05)	0.16
WCST (Perseverative Error)	0.14 (0.04)	0.14 (0.04)	0.14 (0.06)	0.14 (0.05)	0.12 (0.05)	0.16
WCST (Nonperseverative Error)	0.06 (0.04)	0.06 (0.03)	0.06 (0.03)	0.07 (0.04)	0.05 (0.03)	0.92
PVT (RT)	329.8 (43.9)	323.8 (49.9)	327.5 (54.6)	336.9 (60.8)	329.1* (59.3)	0.70
PVT (FS)	5.5 (7.6)	3.6 (4.5)	3.5 (3.7)	2.2 (2.8)	3.5* (3.4)	0.07
PVT (Minor Lapse)	9.9 (8.7)	8.9 (7.3)	10.8 (13.1)	10.5 (9.8)	10.1* (8.2)	0.91
PVT (Major Lapse)	1.3 (2.0)	1.1 (2.3)	1.0 (1.7)	1.3 (1.9)	0.8* (1.1)	0.76
Delayed Memory Recall	5.0 (2.5)	4.0 (1.5)	4.5 (2.1)	4.4 (1.3)	4.1 (2.4)	0.54
Digit Span	17.1 (2.5)	16.9 (3.4)	16.6 (2.6)	16.7 (2.8)	16.9 (2.5)	0.97
BART (Adjusted Mean Pumps)	21.0 (9.8)	20.8 (9.2)	21.9 (10.6)	20.4 (10.6)	18.2 (8.6)	0.42

Note. Values represent means. Those in parentheses represent standard deviations.
*Missing data (N = 12)

Evaluation of Operational Performance

Management of toxic gases. The time taken to complete the management of toxic gases task significantly changed over time ($F(4, 48) = 21.53$, $p < 0.001$; see Figure 3). Post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed that the time decreased from Day 1 ($M = 6.22$ min, $SD = 2.03$) when compared to Day 2 ($M = 4.49$ min, $SD = 1.28$; $p < 0.05$), Day 3 ($M = 4.43$ min, $SD = 0.92$; $p < 0.05$), Day 4 ($M = 3.59$ min, $SD = 0.51$; $p < 0.05$), and Day 5 ($M = 3.55$ min, $SD = 0.72$; $p < 0.05$). Similarly, time decreased from Day 2 when comparing Day 4 and Day 5 ($p < 0.05$), and from Day 3 when comparing Day 4 and Day 5 ($p < 0.05$).

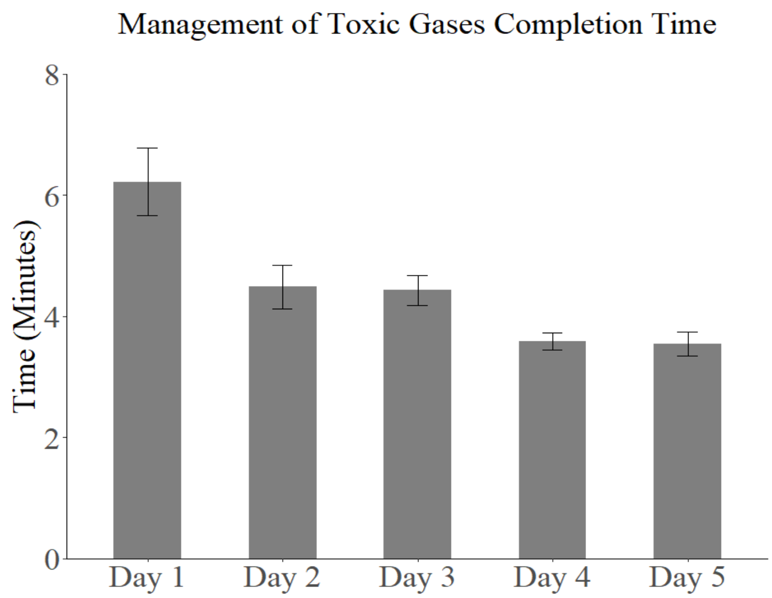

Figure 3. Completion time for the management of toxic gases task. Average completion time (in minutes) for the management of toxic gases task on each day of the DISSUB simulation. Error bars represent standard error of the mean.

No change over time was detected for accuracy in the management of toxic gases task($\chi^2(4, N = 13) = 7.08$, $p = 0.13$). 92.31% of participants reached the correct response on Days 1 and 2 of the simulation, 100% of participants reached the correct response on Day 3, 84.61% on Day 4, and 69.23% on Day 5 (see Figure 4).

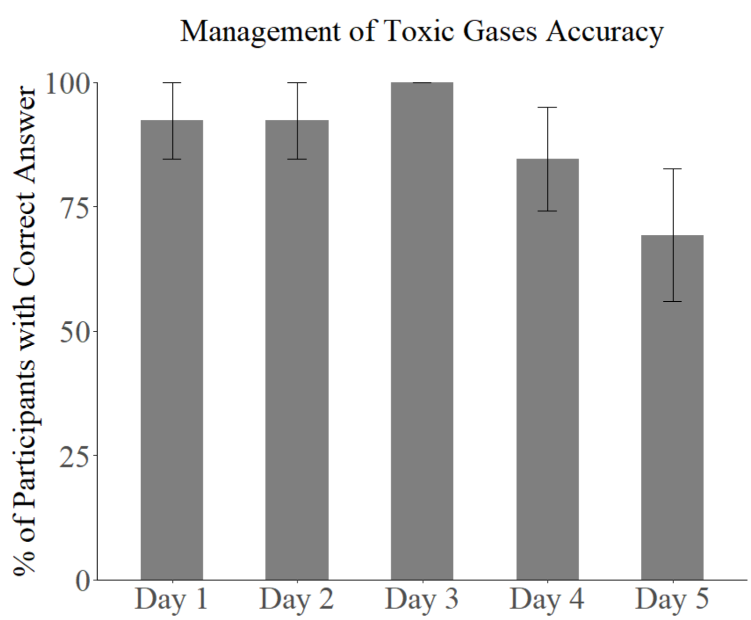

Figure 4. Accuracy on the management of toxic gases task. Percent of participants who reached a correct determination about EAB use on each day of the DISSUB simulation. Error bars represent standard error of the mean.

Carbon dioxide and oxygen stay-time calculations. The time taken to complete the CO_2 and O_2 stay-time calculations task changed over time ($F(4, 48) = 24.26$, $p < 0.001$). Post-hoc pairwise comparisons with Holm-Bonferroni adjustments revealed that the time decreased from Day 1 ($M = 12.62$ min, $SD = 3.23$) when compared to Day 2 ($M = 10.19$ min, $SD = 1.50$; $p < 0.05$), Day 3 ($M = 10.03$ min, $SD = 2.10$; $p < 0.05$), Day 4 ($M = 9.07$ min, $SD = 1.41$; $p < 0.05$), and Day 5 ($M = 7.61$ min, $SD = 1.39$; $p < 0.05$). Similarly, time decreased from Day 2 when compared to Days 3 – 5 ($p < 0.05$; see Figure 5).

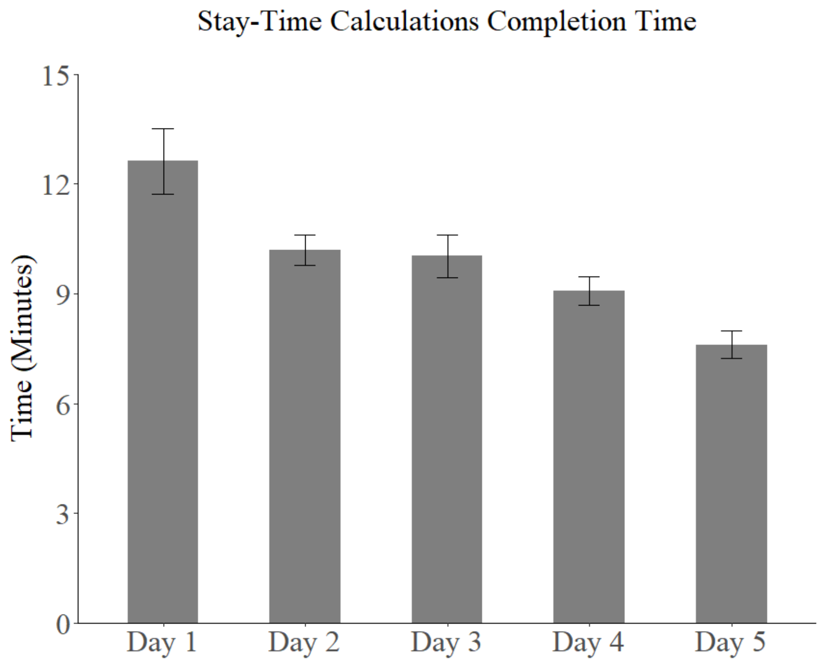

Figure 5. Completion time for the stay-time calculations task. Average completion time (in minutes) for the CO_2 and O_2 stay time calculations on each day of the DISSUB simulation. Error bars represent standard error of the mean.

It was possible for participants to correctly complete the CO_2 portion of the calculations but not the O_2 portion or vice versa; therefore, overall accuracy was counted as correct only for participants who responded correctly to *both* the CO_2 and O_2 calculations. Overall no change in accuracy over time was detected ($\chi^2(4, N = 13) = 3.45$, $p = 0.49$). 38.46% of participants completed the calculations correctly on Day 1, 53.84% on Day 2, 46.15% on Day 3, 30.78% on Day 4, and 61.54% on Day 5 (see Figure 6).

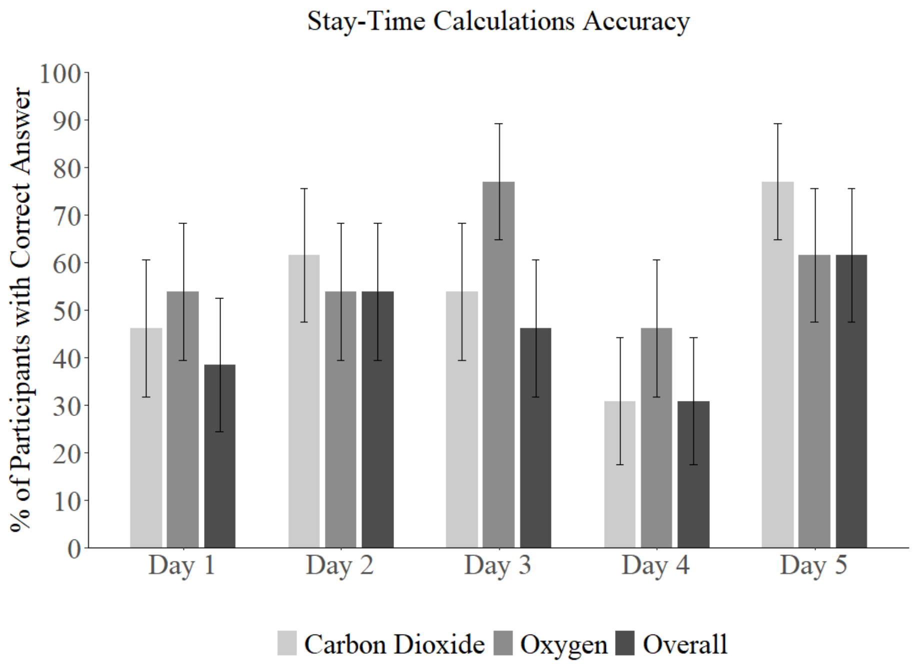

Figure 6. Accuracy on the stay-time calculations task. Percent of participants who reached the correct waiting time for the CO_2 and O_2 stay-time calculations on each day of the DISSUB simulation. Overall accuracy represents participants who reached the correct answer for *both* CO_2 and O_2. Error bars represent standard error of the mean.

Discussion

This study simulated a DISSUB scenario that included a constellation of real and potential environmental, mental, and physical stressors in order to determine their effects on human cognition and operational performance. We have demonstrated, for the first time, that a multi-day, laboratory-based DISSUB simulation experiment is possible, with zero participant attrition. Although our findings did not clearly elucidate the effects of DISSUB-like stressors on performance, they have striking implications for how submariners are trained and how future simulation-based research efforts can maximize their likelihood of success.

Implications for Training

In spite of an expectation that the stressors present in a DISSUB scenario would likely lead to poorer overall cognitive performance (Chabal et al., 2020), the present study did not detect any such performance decrements. However, we have demonstrated that the time to complete operational tasks becomes faster over time, given continued exposure to the tasks. Over the course of the experiment, we observed a reduction in the time it took participants to complete the calculations and reach a conclusion for both the *management of toxic gases* and *CO_2 and O_2 stay-time* tasks. Task performance (i.e., accuracy), however, was not improved. This is notable, as there was no explicit incentive or directive to optimize for time, and the assumption to optimize for accuracy was implicit (i.e., it is necessary for survival). Given these observations, it can be deduced that the *management of toxic gases* and *CO_2 and O_2 stay-time calculations* tasks are associated with a substantial practice effect (i.e., speed increases as users gain more experience with the calculations).

It is crucial that the *management of toxic gases* and *CO_2 and O_2 stay-time calculations* are completed both accurately and quickly during a DISSUB scenario. While accuracy was consistently low on the stay-time calculations in the present study, a recent study by Moslener, Bohnenkamper, and Chabal (2020) identified common sources of poor accuracy on stay-time calculations and made recommendations to improve performance; the submarine force has already begun updating the Guard Book with these recommendations in mind. Evidence from the present study suggests that it may also be possible to improve speed by providing crew members with adequate training on how to complete the calculations. Currently, crew members may complete an optional Senior Survivor Course, in which they are exposed to the DISSUB Guard Book (from which the survival tasks in the present experiment were derived) for two days and are given hands-on practice with the calculations. Ideally, at least 5% of a submarine crew would be trained as Senior Survivors (Whybourn et al., 2019); but even if this percentage is met, it is still possible and likely that the majority of Sailors confronted with a DISSUB scenario have never had experience with the stay-time and toxic gas calculations. The present results suggest that more consistent and extensive training, providing Sailors with the opportunity to repeatedly interact with the calculations present in the DISSUB Guard Book, is likely to increase the speed with which these calculations are completed in the event of an emergency. In combination with Guard Book updates suggested by Moslener et al. (2020), repeated exposure through training would likely increase the chance of survival among crew members in a DISSUB scenario.

Challenges of Simulated Environments

Some plausible explanations for the lack of measurable performance decrements in this study are that: 1) many of the assessments were ordinal scales that are relatively low resolution. These scales may not be sensitive enough to capture subtle performance shifts occurring on such short (i.e., day-to-day) time scales; 2) our relatively small sample size of thirteen might have limited the power of our statistical tests; 3) although there is evidence for stability across multiple administrations of the PVT (Basner et al., 2018), DANA (Russo & Lathan, 2015), Digit Span (Bartels, Wegrzyn, Wiedl, Ackermann, & Ehrenreich, 2010), and BART (White, Lejuez, & de Wit, 2008) some of our other measures may have been associated with practice effects. In the case of the Guard Book tasks this was clearly the case and these effects could have masked the effects of stressors on those tasks.

These null findings are not unprecedented, as similar observations, wherein a majority of assessments related to cognitive performance and psychophysiological measures were not significantly affected during simulated adverse environments, have been reported elsewhere (Cymerman et al., 2002; Eid, Johnsen, Saus, & Risberg, 2004; Slaven & Windle, 1999). Nevertheless, future simulated DISSUB studies should take care to employ high-resolution scales and measures that are sufficiently sensitive to potential changes in performance. All measures, especially stay-time calculations, should be practiced a sufficient number of times for performance to become stable before simulations begin. Finally, large samples should be used to assure sufficient statistical power.

In related studies where certain subscales *did* detect an effect on cognitive performance and/or psychophysiological measures over time, the environments may have been more adverse or realistic than the environment chosen for this exploratory study. For example, one study evaluated participants involved in actual submarine escapes, both in a tank and in the ocean, and was able to detect adverse changes in mood (using the same questionnaire employed here: POMS), ability to fall asleep, and declarative memory (Trousselard et al., 2009). It is reasonable to presume that simulating extended periods of isolation in moderately uncomfortable circumstances, with no perceived life-threatening danger, as was done here, may not provide enough adverse stimulation to elicit decrement to cognitive performance and psychophysiological measures. This is a well-known issue for research involving simulated training (Trousselard et al., 2009), and highlights the importance of the careful manipulation of stressors in a simulated environment.

Although every attempt was made to closely simulate the types of stressors that are expected during a DISSUB scenario (see Chabal et al., 2019), a number of ethical, safety, and logistical constraints prevented us from including all known stressors. For example, we could not ethically expose volunteers to a near-death experience or to the loss of their close shipmates, to unsafe environmental hazards (e.g., hydrogen sulfide), or to intentional pain or injury. Similarly, we could not ethically induce realistic feelings of extreme danger, and participants were aware that they could stop their study involvement at any time. Logistical and space constraints required that subjects were grouped with one or two other participants at a time; this is likely not realistic in a real DISSUB scenario, which will likely involve many more individuals confined to a given area and may thus have a greater effect on cognitive performance and mood (Eid et al., 2004).

Moreover, at the time of experimentation, components of the NSMRL chamber were not certified/ in working order. This led to three main limitations: 1) The chamber could not safely be taken to depth, which prevented us from exploring effects of pressure on cognitive and operational performance. 2) Due to a lack of pressurization in the chamber, the internal lavatory was not functional. Participants were therefore required to enter and exit the test chamber at any time in order to use the restroom, potentially reducing any feelings of confinement. 3) A non-functioning atmospheric control system of the chamber prevented real changes in the environment from being carefully manipulated. As atmospheric and temperature levels could not be safely controlled, they were allowed to freely fluctuate (within a range of safely-acceptable limits). Previous DISSUB research has observed significant effects on performance related to changes in CO_2 and O_2 levels (Cymerman et al., 2002), suggesting that the lack of real environmental changes herein may have contributed to the lack of observed changes in performance over time. Future research in the newly-renovated NSMRL chamber, which should be fully functional by March 2022, will be more able to closely mirror the conditions expected during a DISSUB event.

As with all studies involving human subjects, protection of volunteers from any unnecessary and unreasonable harm is of utmost importance. This requires that researchers do not hastily create simulated adverse environments that may increase the risk of harm, since serious and potentially fatal consequences can occur (House, House, & Oakley, 2000). Thus, while the present DISSUB scenario may not have been fully realistic in terms of the adversity and/or stress associated with life-threatening danger, it provides an important first step to better understand the relationship between certain environmental conditions, cognitive performance, and psychophysiological effects for potentially demanding tasks required for survival. It also demonstrates the logistical feasibility of confining research volunteers to the NSMRL chamber for multiple consecutive days, while maintaining round-the-clock manning to ensure constant safety and adherence to study procedures.

Conclusions and Future Research

The present study successfully conducted a five-day disabled submarine simulation with a 24-hour watchbill that allowed for the continuous collection of data and no participant drop-out. During the simulation, a myriad of environmental, mental, and physical conditions that could lead to DISSUB-like stressors were measured along with cognitive performance, operational performance, and mood. Unfortunately, ethical, logistical, and safety concerns limited the ability to fully replicate a realistic DISSUB scenario. No significant changes in performance accuracy on cognitive assessments or operational measures were observed, but completion time for the operational measures significantly declined throughout the simulation, indicating a practice effect. While this exploratory study provides several notable observations and establishes proof-of-concept for a DISSUB simulation study, it also highlights several research questions that would benefit from future studies. These include the specific effects of individual environmental conditions (e.g., temperature, humidity, pressure, etc.) on human cognitive performance, and the effect of targeted training on crew members' speed *and* accuracy of operational calculations. Additionally, it is important to better understand not only how training regiments can improve performance in a controlled environment, but also any factors present in a DISSUB scenario that could hamper such performance. An understanding of the interplay between environmental factors and cognitive performance can allow training to be further optimized so that crew member survivability in DISSUB scenarios is improved.

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