Acute Exposure to Low-to-Moderate Carbon Dioxide Levels and Submariner Decision Making

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BACKGROUND: Submarines routinely operate with higher levels of ambient carbon dioxide (CO_2) (i.e., 2000 – 5000 ppm) than what is typically considered normal (i.e., 400 – 600 ppm). Although significant cognitive impairments are rarely reported at these elevated CO_2 levels, recent studies using the Strategic Management Simulation (SMS) test have found impairments in decision-making performance during acute CO_2 exposure at levels as low as 1000 ppm. This is a potential concern for submarine operations, as personnel regularly make mission-critical decisions that affect the safety and efficiency of the vessel and its crew while exposed to similar levels of CO_2. The objective of this study was to determine if submariner decision-making performance is impacted by acute exposure to levels of CO_2 routinely present in the submarine atmosphere during sea patrols.

METHODS: Using a subject-blinded balanced design, 36 submarine-qualified sailors were randomly assigned to receive 1 of 3 CO_2 exposure conditions (600, 2500, or 15,000 ppm). After a 45-min atmospheric acclimation period, participants completed an 80-min computer-administered SMS test as a measure of decision making.

RESULTS: There were no significant differences for any of the nine SMS measures of decision making between the CO_2 exposure conditions.

DISCUSSION: In contrast to recent research demonstrating cognitive deficits on the SMS test in students and professional-grade office workers, we were unable to replicate this effect in a submariner population—even with acute CO_2 exposures more than an order of magnitude greater than those used in previous studies that demonstrated such effects.

KEYWORDS: submarines, carbon dioxide, cognitive performance, enclosed environments.

Rodeheffer CD, Chabal S, Clarke JM, Fothergill DM. *Acute exposure to low-to-moderate carbon dioxide levels and submariner decision making.* Aerosp Med Hum Perform. 2018; 89(6):520–525.

Carbon dioxide (CO_2) is a normal constituent of the atmosphere, occurring at a level of approximately 0.04% (400 ppm).[8] Within enclosed, poorly ventilated spaces, however, levels of CO_2 can rapidly rise due to the buildup of metabolically-derived CO_2 generated by the occupants. This build-up of CO_2 can be problematic, as it can lead to hypercapnia (i.e., elevated CO_2 levels in the blood), which is known to have toxic effects at high levels (see Wong[18] for a review). Hypercapnia signs and symptoms include increased depth and rate of breathing, labored breathing, headache, nausea, confusion, impaired cognitive functioning, and, when breathing CO_2 at high levels, loss of consciousness (e.g., Law et al.[7]). To mitigate these toxic effects within the enclosed submarine environment, CO_2 levels are continuously monitored by the central atmospheric monitoring system (CAMs) and controlled through the use of regenerative CO_2 absorbent scrubbers. Submariners, however, are still routinely exposed to elevated levels of CO_2. According to the Nuclear Powered Submarine Atmosphere Control Manual,[9] levels of CO_2 exposure are restricted to 5000 ppm for 90-d limits or 40,000 ppm for both 24- and 1-h limits. While the physiological effects of CO_2 are known at these levels, less is known about how this exposure to CO_2 may affect cognitive performance.

Evidence that raised atmospheric CO_2 levels may have adverse effects on submarine crew performance was noted during the Second World War (WWII), when submariners were

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This manuscript was received for review in September 2017. It was accepted for publication in February 2018.

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DOI: https://doi.org/10.3357/AMHP.5010.2018

typically exposed to prolonged periods of hypoxic hypercapnia during submarine patrols. In 1945, the crew of the USS *Sailfish* was observed over a 68-h period while the boat was submerged to simulate the atmospheric conditions typically encountered during a WWII submarine patrol; CO_2 levels reached 3%, and atmospheric oxygen (O_2) was maintained at 17%. Under these conditions, anecdotal data suggested that submariners' mental efficiency was impaired. It was noted by psychologists onboard that, "The decrement in efficiency of performance is, in general, probably greater and more extensive than appeared during this submergence. … It was clear during the submergence that prolonged attentiveness and connected thinking were adversely affected even in routine and habitual duties."[5] However, although this study observed trained submariners conducting submarine-based tasks onboard an actual submarine, a number of limitations were present. First, the raters and crew were unblinded to the environmental conditions, and many observations were subjective or opinion-based. Additionally, it was not possible to separate out the role of different environmental and procedural factors on performance (e.g., effects of hypoxia vs. hypercapnia, boat temperature, humidity, sleep quality/quantity, boredom) during the prolonged testing period.

After WWII, the main impetus for continuing research into the effects of CO_2 on cognition was provided by the need to set permissible atmospheric limits for the new class of submarines (SSNs), which included design requirements for 55 d of continuous submergence.[5] In 1953, a large-scale formal scientific study (Operation Hideout) was conducted by the United States Navy to investigate the effects of prolonged exposure to low levels of CO_2 in 23 subjects exposed to 1.5% carbon dioxide for 42 d on board the USS *Haddock* (SS231).[5] During Operation Hideout, atmospheric oxygen levels were maintained at 20.5% and control testing periods were conducted on the boat for 9 d before and 9 d after the CO_2 exposure.[4] Results of this study failed to find decrements in problem solving ability, sensory discrimination, complex motor coordination, or alertness during the prolonged CO_2 exposure.

In a recent review of cognitive and behavioral effects of increased CO_2 exposure, it was noted that the findings are inconsistent and at times contradictory.[16] Several contemporary studies have utilized a proprietary test of executive functioning called the Strategic Management Simulation test (SMS), and reported that performance on decision-making tasks may be negatively affected even by low levels of acute CO_2 exposure.[1,11] Satish et al.[11] found that when healthy adults were exposed to 0.1% (1000 ppm) or 0.25% (2500 ppm) CO_2 in an office-like setting they performed statistically worse on several SMS performance parameters compared to when they were exposed to ambient levels (0.06%, 600 ppm) of CO_2.[11] A similar pattern of results was found by Allen et al.,[1] who subjected participants to 550 ppm, 945 ppm, and 1400 ppm CO_2, and found that the same SMS performance parameters became significantly worse as the CO_2 level increased. Earlier research, however, indicates that decrements in other measures of cognitive performance (e.g., longer time to complete reasoning tasks) do not emerge until CO_2 levels reach much higher levels (i.e., 6.5% and 7.5%), and are not present even at 4.5% and 5.5% CO_2.[15] Furthermore, other studies have found null effects of CO_2 on neurobehavioral tests (i.e., redirection, grammatical reasoning, digit span, Stroop test) as well as cognitive tests simulating office work tasks with low CO_2 exposures (e.g., 3000 ppm, 5000 ppm)[23,24] and moderate-to-high CO_2 exposures (e.g., 3–4%).[20,21]

In light of these conflicting findings and the potential serious consequences of mistakes due to impaired cognitive function onboard submarines, it is important that submariner cognitive functioning is examined during exposure to elevated levels of CO_2, such as those routinely encountered during submarine patrols. To date there have been few well-controlled studies that have examined the effects of elevated low-level CO_2 exposures on submariner cognition. The present study aims to resolve the reported discrepancies in the literature and provide empirical evidence to determine whether or not submariners' decision making is adversely affected by acute exposure to levels of CO_2 routinely present onboard submarines.

METHODS

Subjects

There were 36 submarine-qualified sailors (7 officers, 29 enlisted) who participated in our study. Submarine-qualified is defined as having earned either the enlisted or officer submarine warfare insignia (dolphins). All participants were male between the ages of 20 and 47 (Mean = 30.03 yr, SD = 6.86 yr). Women were not excluded from participating, but we received no female volunteers. At the time of data collection, submarine service had only recently opened to women, and there were no women in the local submariner population. The protocol for the present study was approved by the Naval Submarine Medical Research Laboratory's Institutional Review Board. All subjects reviewed and signed informed consent documents before participating.

Materials

Strategic Management Simulation (SMS) test. The SMS test served as our measure of decision making. It is a computer-based platform that collects performance and decision-making data through the presentation of simulated real-world scenarios. It was developed to measure both cognitive and behavioral responses to varying executive functioning task demands. During the test, challenges in the form of simulated real-world events are presented to participants (e.g., fires, floods, conflicts with a local labor union, public unrest). Participants are tasked with responding to these events by communicating their intentions using a drop-down menu of possible decisions and actions (e.g., dispatch fire department/police, request aid). All participants receive the same information at fixed points in simulation time, but participants have flexibility in both the form and time to take actions and make decisions during the simulation. The SMS test has been used to study changes in decision-making abilities under the influence of different drugs, solvents, contamination, stress overload, head trauma, and fatigue during medical residency.[2,13,17] The SMS was developed through the application of complexity theory, which acknowledges the interplay between environmental task conditions and response competencies for thoughts and actions.[12] It attempts to map the decision-making process through the development of time-event matrices, which are created by combining data on information reception, actions taken, and their interconnectedness across time.[16] Past studies reporting on the validity of the SMS as a measure of performance show that SMS test scores are positively correlated with self-reported job performance[15] and faculty assessments of surgical residents.[14]

The SMS provides data profiles on nine specific processing domains for each test taker. Results are reported as raw scores, which are calculated based on the actions taken by the participants, their stated future plans, their responses to incoming information, and their use of prior actions and outcomes. The measures of task performance include speed of response, activity, task orientation, initiative, emergency responsiveness, use of information, approach to problems, planning capacity, and strategy. The raw scores for each domain are linearly related with performance (i.e., higher scores indicate superior performance). In line with Satish et al.,[11] the nine primary scoring domains used in the current study are:

- Basic Activity Level (number of actions taken)
- Applied Activity (opportunistic actions)
- Focused Activity (strategic actions in a narrow endeavor)
- Task Orientation (focus on concurrent task demands)
- Initiative (development of new/creative activities)
- Information search (openness to and search for information)
- Information usage (ability to utilize information effectively)
- Breadth of Approach (flexibility in approach to the task)
- Basic Strategy (number of strategic actions)

Atmospheric chamber. The Naval Submarine Medical Research Laboratory's (NSMRL) Genesis hypo/hyperbaric chamber (23 ft long and 9 ft in diameter) was used as the controlled environment in which we manipulated atmospheric levels of CO_2. Prior to experimental testing, we conducted both unmanned and manned pilot tests to establish procedures for generating and maintaining the targeted CO_2 levels for the required duration of the study. Maintaining the target CO_2 levels was accomplished by adding 100% food grade CO_2 to the ventilation system of the Genesis chamber. The air inside the chamber was circulated to ensure even distribution of CO_2. No additional oxygen was added during the experiment, but fresh air was constantly added at varying flow rates as needed to control the level of CO_2 and maintain atmospheric O_2 at a normoxic level.

Atmosphere monitoring. A mass spectrometer (Model MGA 1100; Perkin Elmer, Pomona, CA) was used to continuously monitor atmospheric O_2 and CO_2 levels in the chamber. The mass spectrometer was connected to two equal lengths of sample line that passed through penetrators in the chamber wall to monitor gas concentrations at either end of the area used for the study. Secondary, precautionary monitoring was conducted using an AMTEK Carbon Dioxide Analyzer (CD – 3A, Applied Electrochemistry, Amatek Inc., Pittsburgh, PA) and an AMTEK Oxygen Analyzer (Model S-3A/I, Applied Electrochemistry, Amatek Inc., Pittsburgh, PA) with Oxygen Sensor (N-22M). The gas sample lines for the O_2 and CO_2 AMTEK analyzers were connected in series and were connected to the chamber through a separate sample line that was positioned on one side of the study area.

The mass spectrometer and gas analyzers were calibrated with primary standard gas mixtures containing levels of CO_2 matched with the intended CO_2 exposure level before each experiment session, immediately before commencing the SMS test, midway through the SMS test, and at the conclusion of each experiment session. The CO_2 and O_2 signals from the mass spectrometer and gas analyzers were sampled at 5 Hz by a MP100 BIOPAC analog to digital data acquisition system (BIOPAC Systems Inc, Santa Barbara, CA). Atmospheric levels were displayed continuously on a computer screen and were stored on the computer hard disk using BIOPAC software (AcqKnowledge version 3.9, BIOPAC Systems Inc, Santa Barbara, CA). In addition to gas levels, temperature and humidity within the chamber were continuously monitored to ensure a comfortable environment for participants. All experiments were conducted at sea level pressure.

Air-quality questionnaire. The chamber environment was also assessed using a subjective evaluation. A five-question environmental quality survey included: 1) three 7-point Likert-type scales asking subjects to rate the quality of the chamber environment in terms of temperature (1 = much too cool; 7 = much too warm), freshness (1 = very dissatisfied; 7 = very satisfied), and odor (1 = very dissatisfied; 7 = very dissatisfied); 2) one 8-point Likert-type scale asking subjects to rate their alertness (1 = feeling alive, vital, alert, or wide awake; 8 = asleep); and 3) an open-ended response question asking, "Are you currently experiencing any physical discomfort? Please describe."

Procedures

Using a subject-blinded design, participants were randomly assigned to one of three acute CO_2 exposure conditions (600 ppm, 2500 ppm, or 15,000 ppm), with 12 submariners in each condition. The number of participants in each testing session ranged from two to four, with one experimenter inside the chamber to conduct the session. After the completion of informed consent and a chamber safety brief, participants entered the exposure environment and began a 45-min atmospheric acclimation period. During this time, participants logged onto their computers, reviewed experimental instructions, received a demonstration of the SMS test, and completed a pretest air quality questionnaire. At the end of the acclimation period, participants completed the 80-min SMS test, then completed a posttest air quality control questionnaire. Participants exited the chamber to be debriefed and thanked for their participation. All data collection sessions lasted approximately 2.5 h and took place beginning at 0800.

Data Analysis

Participants' SMS responses were collected and scored by Streufert, Inc., which was blind to each participant's exposure condition. At the beginning of the study, participants were assigned a unique identification number to enter into the SMS's online administration platform. At the conclusion of the study, the scores for the nine primary scoring domains were provided to NSMRL for each identification number; scores were then sorted to the appropriate exposure condition prior to conducting statistical analysis.

To test our hypothesis that acute exposure to elevated CO_2 would lead to decrements in decision making, we analyzed decision-making performance by conducting a one-way between-subjects analysis of variance (ANOVA) with the three levels of CO_2 exposure (600 ppm, 2500 ppm, and 15,000 ppm) for each of the same nine SMS outcome variables used by Satish et al.[11]

RESULTS

Table I shows the means and standard deviations for the environmental conditions within the chamber for each exposure condition. These data indicate that O_2 within the chamber was successfully maintained at normoxic levels and that the CO_2 exposures closely tracked the desired levels. Three separate one-way ANOVAs were used to analyze temperature, humidity, and barometric pressure. Temperature ($P = 0.12$) and barometric pressure ($P = 0.48$) did not significantly differ across conditions. Humidity, however, did significantly vary [$F(2, 9) = 10.31$, $P = 0.005$]. Higher humidity corresponded with higher CO_2 levels, and can most likely be attributed to differences in the chamber ventilation rates between CO_2 conditions. As CO_2 level increased across conditions, less ventilation was required to maintain the desired atmospheric CO_2 levels.

To determine whether these differences in humidity led to different perceptions of air quality (i.e., freshness) between conditions, we conducted a mixed-model ANOVA with participants' perception of air quality (pre- and posttest) as the within subjects variable and exposure level as the between subjects variable. Perceptions of air quality did not differ significantly between conditions [$F(2, 33) = 0.86$, $P = 0.43$], suggesting that the differences in overall humidity and CO_2 exposure level were not discernible between the three groups exposed to the different CO_2 exposures. Additionally, examination of the means for perceived air quality revealed that all conditions fell around the midpoint of the scale (i.e., 4 on a 7-point scale), indicating a neutral perception of air quality across the three CO_2 exposure conditions. These data suggest that subjects did not experience marked differences in symptomology between the high and low CO_2 exposure conditions, and thus were unlikely to be aware of acute changes in atmospheric CO_2 up to the levels used in the current study.

Cognitive performance was not found to differ between the three levels of acute CO_2 exposure for any of the SMS measures (all F values < 0.95, all P values > 0.4; see **Table II**). Effect size values were small (all η^2_p values < 0.06). Although these effect sizes represent only the effect from the current study (derived from our sample of submariners), it is possible to use confidence intervals to estimate the overall population effect size. Using the MBESS package in R[6], we were able to determine with 95% certainty that the population effect size is smaller than 0.18 for all of our measures (see **Table III**).

In order to determine the observed power and the sample sizes that would be required to obtain significance at the observed effect sizes, a power analysis was conducted using the pwr package[3] of R. To compute observed power, the pwr.anova.test function was used for a balanced one-way ANOVA with 3 groups of 12 subjects and an alpha level of 0.05. Cohen's f was computed based off of the reported partial eta squared (η^2_p) reported by SPSS. Observed power ranged from 0.06 to 0.21, indicating that our sample size would not have been sufficient to detect significance at $P < 0.05$. In order to determine the sample size that would be required to detect significance, we used the pwr.anova.test function with 3 groups, an alpha level of 0.05, Cohen's f derived from observed η^2_p, and an assumed power of 0.80. Required sample size ranged from 171 to 9627. See Table III for full statistics.

DISCUSSION

When acutely exposed to operational levels of CO_2 (600 ppm, 2500 ppm, and 15,000 ppm) in an enclosed environmental chamber, submariners did not experience any deficits in decision-making ability, as measured by performance on the SMS test. Our findings are in contrast to past research utilizing the SMS test,[1,11] in which cognitive deficits were observed at low-to-moderate levels of CO_2. At 2500 ppm, for example, Satish et al.[11] reported a robust negative effect of CO_2 on SMS test performance. When compared to a normed distribution of SMS performance, the measures of initiative, information usage, breadth of approach, and basic strategy were all at or below the 25th percentile, which is considered dysfunctional (see Satish et al.,[11] Figs. 2–11). Even at six times this level of CO_2 (i.e., 15,000 ppm), we were unable to detect any decrements in decision-making performance.

An examination of the means across our three test conditions reveals no trends or indicators that performance was at all affected by elevated CO_2 exposure (see Table II).

Although we did not have access to the normed SMS performance database to make exact assessments of where our results fall on the distribution, a

Table I. Atmosphere Readings* by Condition.

CONDITION	CO_2 (%)	O_2 (%)	TEMP (°C)	HUMIDITY (%)	BAROMETRIC PRESSURE
600 ppm	0.064 ± 0.008	20.94 ± 0.05	22.09 ± 0.33	39.22 ± 5.79	757.76 ± 6.92
2500 ppm	0.249 ± 0.010	20.83 ± 0.07	23.89 ± 0.11	53.46 ± 2.03	762.98 ± 4.52
15,000 ppm	1.510 ± 0.019	20.50 ± 0.07	24.03 ± 0.08	78.26 ± 2.02	761.89 ± 6.81

* Means ± SD.

Table II. One-Way ANOVA Results.

OUTCOME VARIABLES	CONDITIONS (ppm of CO_2)* 600 ppm	2500 ppm	15,000 ppm	F(2, 33)	P	η^2_p
Basic Activity	89.92 ± 31.62	83.42 ± 28.28	89.58 ± 21.47	0.21	0.81	0.013
Applied Activity	54.58 ± 24.24	50.33 ± 30.43	51.58 ± 18.20	0.09	0.91	0.005
Focused Activity	12.33 ± 4.48	12.25 ± 4.14	11.50 ± 3.00	0.16	0.85	0.010
Task Orientation	90.33 ± 35.44	75.33 ± 31.84	88.50 ± 28.86	0.78	0.47	0.045
Basic Initiative	13.92 ± 7.19	12.33 ± 8.28	17.58 ± 12.52	0.94	0.40	0.054
Information Orientation	9.08 ± 9.22	5.83 ± 6.02	8.92 ± 7.46	0.68	0.51	0.040
Information Utilization	8.58 ± 5.05	7.58 ± 3.87	8.58 ± 5.43	0.17	0.84	0.010
Breadth of Approach	7.83 ± 1.47	7.75 ± 1.06	7.83 ± 1.03	0.02	0.98	0.001
Basic Strategy	16.58 ± 11.02	16.08 ± 12.13	16.00 ± 11.22	0.01	0.99	0.001

* Means ± SD.

comparison of our observed mean raw scores to those reported by Satish et al.[11] suggests that SMS performance falls between the 50th and the 75th percentile; this indicates average decision-making performance for each of our three submariner groups. Furthermore, none of the raw mean scores on the SMS performance parameters fell below the 25th percentile.

The effect sizes observed in the present study were low (η^2_p ranging between 0.001 and 0.054). In other words, the level of CO_2 that each subject was exposed to can only explain between 0.1% and 5% of the variance in SMS results between groups. Using these values, a post hoc analysis of the current data indicated that our study would have required 171 to 9627 subjects per group to achieve a power level of 0.80 at an alpha level of 0.05. The large subject numbers required to achieve high power and the small effect sizes observed in the current study suggest that any potential changes in cognitive function attributed to CO_2 exposure are of little practical importance. Furthermore, given that the current results showed no trend for a decrease in cognitive function with increasing CO_2 exposure (despite employing a high CO_2 condition that was more than an order of magnitude greater than that reported to show significant cognitive decrements in the original Satish et al., study), it is unlikely that our null findings were the result of a Type II error.

One way to potentially increase study power without increasing sample size would be to conduct within-subject analyses by exposing participants to each of the three CO_2 conditions. This might have improved sensitivity for low-magnitude effects that may have been masked by interindividual variability within groups. In our present study, a within-subject design was not feasible; submariners' operational schedules made it difficult to ensure that subjects would be able to report to the lab for three separate testing sessions. However, even if a within-subject design had been possible, it is unlikely that our results would have been different as our results are consistent with recent within-subject research conducted by NASA.[10]

Ryder and colleagues[10] performed a randomized, double-blind, repeated measures study in which 22 individuals were exposed to each of four acute CO_2 exposure conditions (600 ppm, 1200 ppm, 2500 ppm, and 5000 ppm). Although nominal SMS performance decreases were observed from 600 to 1200 ppm, performance recovered or even improved at higher concentrations. Even when performance dipped at 1200 ppm, it was never reduced below average (50th to 75th percentile). This concurrence with our present results provides additional evidence that our inability to replicate Satish et al.[11] is not due to methodological or statistical failure.

The diversion of our results from that of work demonstrating SMS impairments at low-to-moderate levels of acute CO_2 exposure may be the result of our subject population's previous occupational exposure to chronic low levels of CO_2. Submarines routinely operate with levels of CO_2 around or above 2500 ppm for sustained periods of time. A typical deployment for a submarine can last up to 3 mo. Depending on mission demands, opportunities to come to the surface and ventilate (i.e., refresh the boat's air with that from the outside) may be rare. Speculatively, submariners may develop a physiological tolerance to elevated levels of CO_2, resulting in protection against the cognitive deficits observed in a normal population. This explanation is unlikely to fully explain our results, however, an increasing number of studies in healthy college students[19,20] and middle-aged adults between 31 and 53 yr of age[10] have similarly failed to show significant cognitive changes during acute exposure to 1000 ppm – 5000 ppm CO_2. Nevertheless, additional research would be required to determine if previous exposures to chronic low levels of CO_2 impart a tolerance, or adaptive response, that would mitigate any potential cognitive deficits resulting from subsequent acute CO_2 exposures. One way to probe CO_2 tolerance might be through the use of objective physiological measures (e.g., heart rate, respiratory rate, oxygen saturation) in concurrence with cognitive testing. If submariners display blunted physiological responses to acute CO_2 exposure,

Table III. Power Assessments on SMS Outcome Variables.

OUTCOME VARIABLE	F	P	η^2_p	95% CI FOR η^2_p	COHEN'S f	POWER	N REQUIRED FOR POWER OF 0.8
Basic Activity	0.21	0.81	0.013	0-0.076	0.11	0.08	735
Applied Activity	0.09	0.91	0.005	0-0.031	0.07	0.06	1920
Focused Activity	0.16	0.85	0.010	0-0.061	0.10	0.08	957
Task Orientation	0.78	0.47	0.045	0-0.160	0.22	0.18	207
Basic Initiative	0.94	0.40	0.054	0-0.175	0.24	0.21	171
Information Orientation	0.68	0.51	0.040	0-0.149	0.20	0.17	234
Information Utilization	0.17	0.84	0.010	0-0.065	0.10	0.08	957
Breadth of Approach*	0.02	0.98	0.001	0-0.015*	0.03	0.05	9627
Basic Strategy*	0.01	0.99	0.001	0-0.037*	0.02	0.05	9627

* 95% CIs could not be computed for Breadth of Approach or Basic strategy, as values were too close to zero. 97% and 99% intervals are reported, respectively.

it might suggest that their repeated chronic exposures have led to adaptation that mitigates CO_2's cognitive effects. Future research should explore this possibility.

Future research should also investigate the effects of acute exposure to low-to-moderate levels of CO_2 using other available, validated tools for examining performance. A limitation of the SMS test is that it is a commercialized, proprietary instrument. As a result, details on how the outcome variables are calculated are not easily accessible to researchers. Using well-validated and reliable test instruments that provide detailed information on how test parameters are scored and how they are related to cognition or decision making would allow for a clearer interpretation of data. It will also be important for future research to consider how elevated levels of CO_2 may affect submariners' performance on a job for which they are highly trained and that they perform on a regular basis. An ideal future study would include both operational tasks and validated measures of cognition.

In conclusion, our findings failed to replicate the impaired decision-making performance reported by Allen et al.[1] and Satish et al.[11] during acute exposures to CO_2 at 2500 ppm; however, our results are in concurrence with more recent research reporting null effects at low-to-moderate levels of CO_2 on both the SMS test[10] and on traditional measures of cognitive and neurobehavioral function.[19,20] Overall, results suggest that there is no effect of acute CO_2 exposure on submariner decision-making performance at levels routinely experienced during submarine operations. Future research, however, should explore the relationship between CO_2 exposure and submariner cognitive performance at higher levels of CO_2 that may be present in the submarine atmosphere during emergency situations, where errors or poor decision making may have critical consequences. When conducting these studies, it will be necessary to employ reliable and validated measures of cognitive performance that attempt to reflect the tasks and duties of submariners, to better understand the impact of CO_2 exposures on operational performance.

ACKNOWLEDGMENTS

The views expressed in this article are those of the author and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government. The study protocol was approved by the Naval Submarine Medical Research Laboratory Institutional Review Board and is in compliance with all applicable Federal regulations governing the protection of human subjects. This work was funded by Office of Naval Research work unit number F1402. Special thanks to Ms. Sharon Driscoll for assisting with data collection and to the Navy Divers who supported this project supervising the Genesis Chamber life support systems.

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