Cardiac Biosignal and Adaptation in Confined Nuclear Submarine Patrol

B. Lefranc, C. Aufauvre-Poupon, C. Martin-Krumm, M. Trousselard

***Abstract*—**Isolated and confined environments (ICE) present several challenges which may adversely affect human's psychology and physiology. Submariners in Sub-Surface Ballistic Nuclear (SSBN) mission exposed to these environmental constraints must be able to perform complex tasks as part of their normal duties, as well as during crisis periods when emergency actions are required or imminent. The operational and environmental constraints they face contribute to challenge human adaptability. The impact of such a constrained environment has yet to be explored. Establishing a knowledge framework is a determining factor, particularly in view of the next long space travels. Ensuring that the crews are maintained in optimal operational conditions is a real challenge because the success of the mission depends on them. This study focused on the evaluation of the impact of stress on mental health and sensory degradation of submariners during a mission on SSBN using cardiac biosignal (heart rate variability, HRV) clustering. This is a pragmatic exploratory study of a prospective cohort included 19 submariner volunteers. HRV was recorded at baseline to classify by clustering the submariners according to their stress level based on parasympathetic (Pa) activity. Impacts of high Pa (HPa) versus low Pa (LPa) level at baseline were assessed on emotional state and sensory perception (interoception and exteroception) as a cardiac biosignal during the patrol and at a recovery time one month after. Whatever the time, no significant difference was found in mental health between groups. There are significant differences in the interoceptive, exteroceptive and physiological functioning during the patrol and at recovery time. To sum up, compared to the LPa group, the HPa maintains a higher level in psychosensory functioning during the patrol and at recovery but exhibits a decrease in Pa level. The HPa group has less adaptable HRV characteristics, less unpredictability and flexibility of cardiac biosignals while the LPa group increases them during the patrol and at recovery time. This dissociation between psychosensory and physiological adaptation suggests two treatment modalities for ICE environments. To our best knowledge, our results are the first to highlight the impact of physiological differences in the HRV profile on the adaptability of submariners. Further studies are needed to evaluate the negative emotional and cognitive effects of ICEs based on the cardiac profile. Artificial intelligence offers a promising future for maintaining high level of operational conditions. These future perspectives will not only allow submariners to be better prepared, but also to design feasible countermeasures that will help support analog environments that bring us closer to a trip to Mars.

***Keywords*—**Adaptation, exteroception, HRV, ICE, interoception, SSBN.

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I. Introduction

The operational capacity of SSBN depends on maintaining the capabilities of the crews at the highest level in a singular professional environment which combines the characteristics of both an ICE and an Extreme and Unusual Environment (EUE). The literature shows that the constraints of ICE and EUE can upset the balance between the demands of the environment and the resources mobilized by individuals, leading to changes in the individual-environment relationship. Reference [1] indicated, with respect to the extreme nature of certain situations, that « the individual is placed in circumstances with intense emotional potential or requiring an adaptive response, an adjustment, which he experiences as beyond his means ». The individual underpins the existence of a consubstantial link between man and his environment. These two are elements of the same system, the characteristics of one being inevitably linked to the characteristics of the other and to those of the overall system. The ICE and EUE expose the crews who encounter them to cognitive, psychological, and sensory disturbances. The exceptional nature of these terrains means that individuals participating in missions must experiment and implement several processes to adapt. The adaptation of an individual to the environment implies a permanent interaction with the world, which is constantly changing. This adaptation is ultimately inseparable from the response to stress. In particular, the SSBN adds a stress factor that makes its crews exceptional. Operational constraints impose confinement and isolation conditions, chronobiological constraints, promiscuity, and an alternation between an impoverishment and an over-stimulation of the senses on submariners during patrols. Consequently, there is a challenge to maintain well-being, performance, and operational capabilities at the highest level. The study of the individual impact of the SSBN environment highlights multiple consequences on sensory perception, cognitive performance, sleep, thymia, and social adaptation. In consequence, there is a decrease in the submariners' ability to adapt to the stress they face. Preventing, limiting, or mitigating this stress is a necessity to ensure the increased well-being and performance of submariners, which leads to mission success. The literature highlights promising leads but remain limited to be considered effective and integrated into the submariners during patrols.

The literature is also discreet in terms of perceptual processes. Few studies focused on the analysis of HRV as a marker of adaptation of the operational constraints faced by submariners [109]. To our knowledge, no studies exist on the impact of stress during a patrol on SSBN on the psychosensory of submariners. In addition, limited data are available on submarine patrol tracking. Data are often not widely available to the scientific community, which is an important military defense issue. This paper has the aim of discussing the use of HRV as a marker of adaptation among submariners of the French Navy. The main objective of this study is to evaluate the impact of stress on the mental health and sensory degradation of submariners during a mission on SSBN by considering the interindividual differences to stress adaptability. A better understanding of the impact of these deleterious situations on the psychosensoriality of individuals dealing with these exceptional situations is the key to considering the development of relevant countermeasures.

II. Related Studies

A. ICE/EUE: An Exceptional Environment

ICE/EUE environments are professional operational environments experienced by astronauts, polar winterers, or submariners through professional engagement. They are marked by extreme climates, danger, limited facilities and supplies, isolation of loved ones, and required interaction with others [2]. Recently, [3] characterized these environments by situations that place high demands on the individual's physiological, emotional, cognitive, and/or social treatment resources. Data from historical and analogous space flights, such as research stations in Antarctica and space missions suggest that prolonged periods of social and sensory monotony can have a negative impact on human psychosocial health [4], [5]. Many studies have shown in confined environments that they are the cause of many disorders, such as somatic symptoms (e.g. fatigue, headaches, weight gain, gastrointestinal complaints, rheumatic aches and pains), sleep disorders (e.g. difficulty falling asleep or staying asleep, changes in circadian rhythms), mood disorders (e.g. anger, irritability, anxiety), psychiatric disorders (e.g. depression, personality), increased tension and conflict between crew members or with people outside the group [6]-[10]. Cognitive problems have also been reported such as a decrease in precision and short-term memory, increased reaction time, difficulty concentrating, suggestion sensitivity, intellectual inertia, disturbance of vigilance [11], [12]. Reference [13] also showed that isolation and confinement resulted in a decreased ability to regulate emotions, as well as an increased vulnerability to negative emotions. Rohrer's [14] three-step adaptive phase model considers the effects of isolation and confinement in extreme environments on crew members' emotions, performance, and interpersonal relationships. It shows an increase in anxiety and nervousness, followed by an increase in depression due to monotonous daily life and finally, the appearance of obvious hostility. The environment of the SSBN, called *inner* space compared to the *outer* space of the astronaut, has several similarities [15]. The submarine environment represents the most stressful and psychologically demanding forms of military service, isolated, confined, and extreme, highlighting issues of privacy, territoriality, and resource use conflicts [16], [17]. Individuals on board a SSBN live with nuclear arm and fear of potentially lethal damage.

B. Stressors of a Patrol on SSBN

Selye [18] was the first to define stress as « a response to change in order to maintain the state of stability or homology that the body has maintained against the stimulus to break the mental and physical balance and stability of the body ». Lazarus and his colleague [19] introduce a cognitive dimension by specifying that it is the subject's perception of the situation that gives the event the character of a stressor when it leads to an imbalance between the demands of the environment and the individual's resources to cope with it. This process corresponds to the physiological modifications allowing a return to homeostasis in relation to the requirements of the environment. Improperly adjusted physiological activation has a functional cost to the body. The study of HRV has become widely accepted as one of the markers of an individual's response to stress [20]. It has been validated as an objective method for evaluating stress [21], [22], even in ICE/EUE environment [23], and integrated in militaries research [24], [25]. Responses to the environment are caused by changes in activity in the sympathetic, parasympathetic, and enteric components of the visceral motor system that govern the smooth muscles, heart muscle and glands of the body. These systems play a major role in allowing sympathovagal balance and thus contribute to the maintenance of adaptive homeostasis. Porges [26] described HRV as an index not only of chronic stress, but also of vulnerability to stress. This means that the higher the HRV is, the more the body and the mind will be resistant to a psychological or physical stressor.

Stressors related to extreme environmental conditions are relatively little studied. Research on the impact of ICE and EUE environments shows evidence of stress maladaptation [27], [28]. Earls [29] defined the stressors experienced by a submariner on patrol as multifaceted. These stressors are linked not only to environmental constraints (isolation, confinement, absence of day/night cues, monotony in routine, lack of communication with the outside world, extended separation from family members) but also on work specifications (watchkeeping rhythm, operational cycle, hostile environment, nuclear weapons). Recently, Brasher et al. [30] found that over-commitment and rank are predictors of stress in submariners. The operational constraints to which submariners are subjected alter higher neurocognitive functions [31], cause emotional blunting [32], emotional and thymic disorders [33], [34], decreased job performance, psychosomatic complaints, interpersonal conflict, loss of attention and emotional lability, psychiatric disorders including depression and anxiety [15], [35], significantly disrupt [36], or not sleep [37], and lead to disorientation in time and space during patrols [38]. However, these constraints are not inseparable from the passage of time. There is empirical evidence of the existence of specific critical phases during missions in ICE/EUE environments. Time itself would be a source of stress, the intensity of which would vary among stages during the mission [39]-[44]. The cycling pattern associated with the operational constraints are related to the winter-over syndrome [45]. There is a pattern of winter-over syndrome or seasonal affective disorder during a SSBN patrol, particularly for watchkeeping submariners with interindividual differences. Moreover, symptoms seem to increase after the midpoint of the mission, with some reduction in symptoms toward the end. This pattern is known as third-quarter phenomenon [46]. The pace of the SSBN's patrol places a high demand on submariners' adaptation. Such a naturalistic stressful environment should help to better understanding interindividual differences in dealing with stress.

C. Adaptation to Stress and Sensory

The stress response is consubstantial with living organisms, with interactions with the environment being characteristic of its dynamics. The individual is transformed by his interaction with the world [47]. The individual gives « shape to his environment », he « is at the same time shaped by it ». Each event leaves a trace in the brain due to the emotion generated consciously or unconsciously, and any intense and/or prolonged stress permanently transforms the brain morphology. This enaction is mediated by interception, which informs the subject at every moment on his state of homeostasis with regard to the solicitations induced by the dynamics of the living world and exteroception, which inform the subject on the state of the environment. This sensory inscription in the environment contributes to the quality of the stress response and the maintenance of the submariners' health. Adaptation is necessary to enable the individual to successfully manage the stressors typical of extreme environments [17]. Many factors may affect inter-individual differences to cope successfully with extreme environment [35], [48]. Unpleasant emotional reactions resulting from the individual's interpretation of the environment have been found to be the most frequently reported stress stimuli. Several researchers have argued that the crucial determinant of the stress response is not the environment itself but rather the meaning that the individuals attach to their experiences [49]. The perception of the body actively participates in the adaptive response of subjects in situations of physical and psychological environmental constraints [50]. The impact of this perception is the subject of many studies to better understand the emergence of psychopathologies. These studies show that evaluating the intensity of an environmental challenge or the seriousness of a cerebral dysfunction related to a psychopathology, amounts to judging the quality of self-perception, via body dysperception. Little explored in the healthy subject under constraint, a certain number of theoretical and experimental arguments underline its role on the emotional psychic [51], [52], thymic [53], [54], attentional [55], [52], cognitive [56], and social functioning [57]. Perception of the body involves the processing of sensory information, or sensory integration, and refers to the process by which the brain receives a message through the senses and transforms it into an adapted behavioral response. It is defined as the appropriate use of sensory inputs from the body's receptors [58] and according to [59] involves two mechanisms. Modulation allows the facilitation of certain messages to produce more responses and the inhibition of other messages to reduce excess activity [58]. Discrimination is characterized by the ability to distinguish between different stimuli and to interpret their characteristics [60]. Each of these modalities essentially plays two roles: ensuring survival (modulation) and relating to the environment (discrimination). While these two functions are essential to the individual's adaptation to his or her environment, they are modulated in terms of perception and interpretation of environmental sensory stimuli according to our receptors, our tolerance threshold, our ability to modulate inputs as well as our previous experiences and the emotional context in which they are exercised at any given moment [59]. Sensory stimuli, vectors of environmental or bodily information, are multiple and can be analyzed in terms of modality, duration, and intensity. They are modulated by sensory receptors that rely on proprioceptive, interactive and exteroceptive sensitivity mediated by our five senses, each forming interaction loops involved in alliesthesia [61]. This term links the sensations coming from the inside with the outside [62], as well as their mutual interactions. These receptors are closely related to five major brain structures including the spinal cord and brain stem, the thalamus, the limbic system (i.e., amygdala, hippocampus), the cortex and the cerebellum [63]. This dynamic process contributes to the maintenance of homeostasis. ICE/EUE environments, characterized by sensory monotony, alternating between over and under stimulation, weaken this balance necessary to maintain the health of submariners during their SSBN patrol.

D. Sensory Dysfunctions between Depletion and Over-Stimulation of the Environment

The literature emphasizes the role of sensory perception in stress adaptation, cognitive functioning, and social relationships. Sensory dysfunctions are mainly studied in the elderly and children with neuropsychiatric problems. Elderly people are subject to sensory loss marked by the aging of the body. Studies report disorientation, increased vulnerability to stress through lack of adaptive strategies, lowered self-esteem, lack of confidence, decreased communication, cases of anxiety, lethargy and social dissatisfaction, frustration, and flare-ups [64]-[66]. Decreased functional capacity, physical health and strength are also important concepts associated with sensory loss. These people experiment mood changes and depression, impacting the quality of life and the feelings of well-being [66]. In children, three types of disorders related to the different stages of the sensory information processing process are described [67]. Modulation (intake) results from a problem in the initial phase of information processing depending on the activation threshold at which this recording occurs disorganizing attentional, motor and/or emotional behavior. Discrimination (interpretation) reflects a problem in interpreting quality and distinguishing sensory information resulting in difficulties in perceiving differences and similarities between sensations. Furthermore, it is reported that good sensory discrimination is a good representation of body schema. Interaction with the environment involves motor disorders of sensory origin (e.g., postural disorder, dyspraxia) leading to problems with postural stability and planning of motor sequences in response to sensory demand. These sensory disorders produce responses that are not adapted to the environment and interfere with daily functioning and participation in occupations in diverse contexts.

The literature on ICE and EUE environments describes, in conjunction with changes in the sensory stimuli of the living environment, emotional and thymic disturbances [34], [68], attentional and cognitive [31], [32], and social [69] that underlie maladaptive stress responses [31], [36]. These disorders appear during missions in its environments in individuals without any malfunctioning of the sensory sensors. All these data suggest that immersion in these non-ecological professional sensory environments could have deleterious effects on physical, mental, and cognitive health through mechanisms affecting sensory integration and inappropriate stress responses. Sensory deprivation related to biological changes in the neurological structure of the brain, psychological, physiological changes (e.g., intellectual disorders, anxiety, decreased motivation, sleep disturbances, somatic and emotional complaints) may cause individuals to feel disconnected from reality [70]-[72]. In analog environments, monotony imposed by the lack of sunlight and confined space, lack of sensory variation and novelty, boredom constitutes a major stressor leading to a decline in the neural plasticity of the brain [73], [74], even more than over-stimulation [49]. Kubzansky [75] defined the main dimensions of depletion and over-stimulation, including intensity (loudness), diversity (variation in stimulation and patterning (elimination of patterned visual information). A variety of senses can be affected, including the visual, auditory, olfactory, kinesthetic, gustatory, and tactile systems, even to the point of altering the concept of time. He also speaks of a generally disorganizing effect of deprivation on both the inter and exteroceptive perception. However, it must be said that exteroceptive and interoceptive perception is little explored in the healthy subject. Recent work points to an alteration of sensory perception in SSBN [76], [77]. In view of these preliminary findings, extreme situations would endanger the equilibrium of those individuals least prepared for the changes inherent in the situation. They « create a special relationship between the person and his/her environment, which the person considers to be beyond his/her capacities and endangers his/her well-being » [19]. Characterized by high levels of stress, they are stress-generating. Individuals with an extraordinary destiny evolving in these environments where monotony reigns are subject to a significant restriction of sensory stimuli, a low diversification of physical stimuli, and a limited social environment [78]. Submariners sailing in the shadows dressed in a new role, unique and professional, assigned for the mission, forget everything that might have existed before [79]. The stress they experience while on patrol due to the constraints of the environment and the mission force them to adapt to survive. Physiological and psychological disorders in such environments can have detrimental consequences [80], [81]. Our main hypothesis is that the patrol will have a more deleterious impact on the psycho-sensory functioning of the LPa group than on the HPa group. We make the secondary hypothesis that the recovery is less efficient for the LPa group compared to the HPa group.

III. Material and Method

A. Design

This is a pragmatic exploratory study of a prospective cohort conducted with the submariners of the SSBN « Le Triomphant », scheduled for a 60 to 80-day patrol in autumn/ winter 2017-2018 SSBN mission dates classified confidential-defense. It was submitted to the Committee for the Protection of Persons Southeast VI (Clermont-Ferrand) and received a favorable opinion on September 15, 2017.

B. Participants

29 male submariners of the SSBN « Le Triomphant », red crew, were recruited by the ship's doctor who presented the study, its objectives, and constraints during a briefing at the beginning of the mission preparation phase. Inclusion criteria were based on the suitability of subjects deemed fit for submarine navigation (decree of July 18, 2014) according to the regulations in force within the Armed Forces Health Service (IM n°600). In particular, the subjects all had a normal audiogram showing good hearing.

C. Data Collection

The Socio-biographical Questionnaire (SbQ, 16 items) collects standard socio-demographic data such as age, health status, specialty in the navy, pace of work, number of diving hours, hobbies. The Scale of Positive and Negative Experience Questionnaire (SPANE, 12 items) was used to assess subjective feelings of well-being based on how frequently they were felt over the previous four weeks [82]. The Multidimensional Assessment of Interoceptive Awareness (MAIA, 32 items) assess the interoceptive awareness in eight sub-factors measuring sensitivity to body sensations, uncomfortable, comfortable and neutral, emotional reaction and attentional response to sensations, ability to regulate attention and awareness of mind-body integration [83]. The Sensory Gating Inventory (SGI, 36 items) evaluated abnormal perceptual salience in 4 sub-factors measuring perceptual modulation, sensory inclusion, sensory distractibility, and sensory fatigue [84].

Vision was assessed by the Parinaud's Test, which measures the accommodation distance using a tape measure of the natural distance (from the tip of the nose to the reading surface) at which the subject holds a text to read it comfortably (paragraphs written with decreasing font size). The suggested reading distance when working on visual acuity is 33cm with a tolerance of 30 to 35 cm. A luminance control was performed at each luxmeter test to ensure that the lighting environment was the same for all subjects.

The Loudness Discomfort Level (LDL) is a commonly used test in the hearing evaluation of patients with possible intolerance to sounds. The LDL in normal hearing subjects is evaluated using pulsed ascending tones in the frequencies of 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 6000 Hz until the individual referred beginning of discomfort. About 90% of the subjects referred discomfort for intensities between 90 and 105 db. When there is a suggestive history of sound intolerance, the altered LDL stresses the hyperacusis suspicion. As there is a great variability in the LDL results, it is important that the LDL is adapted for those individuals in order to assist the differentiation between misophonia and phonophobia, that may be associated to hyperacusis. There are no reports in the literature about risks to the hearing resulting from the LDL application, but as patients with sound intolerance fear intense sounds exposure, they must be previously assured about the control of the sound intensity to which they will be exposed, so the test will be reliable. LDL was recorded using the ELECTRONICA 600M. Each stimulus was presented during approximately two seconds with an interval of approximately one second between each presentation, until the subject referred initial discomfort with the intensity sensation. The instruction is a determinant part in the type and the quality of response. All volunteers of the research will be placed in the quietest room and will receive the following instruction: « You will hear sounds that will become stronger. Please raise your hand when the sound reaches an intensity that you no longer want to hear it, and the sound will stop immediately. The aim of this test is to know which sound intensity provokes discomfort and not to know if the sound is strong or weak. The sound can be strong and not provoke any hearing discomfort, for example ».

RR interval data were recorded during five minutes in a sitting position using an electrocardiogram (ECG), at a sampling frequency of 250 Hz (Codesna, Physioner). Leaning against the skin, two electrodes, attached to each wrist by a clamp, pick up the electrical signals from the heartbeat and send the information in real time to the Physioner software by Bluetooth. The analysis of the HRV was done according to the guidelines, considering possible circadian variations, using the PyHRV library (Python). Subjects were controlled in the following elements: weight, height and waist-to-hip ratio, smoking, alcohol (> 24 h), caffeinated, coffee, tea beverages (> 1 h), food (> 2 h), physical activity (> 12 h) and quality of sleep on the experimental day and the day before. The raw ECG data were filtered, and R peaks detected automatically using the BioSPPy library (Python). The validity of R wave detection was manually examined to ensure that they had been correctly detected. Also, the RR-intervals were manually corrected for artefacts and ectopics using linear interpolation.

Time domain analysis. Time domain HRV metrics included mean R-R (mean interbeat interval), SDNN (standard deviation of normal to normal R-R interval), RMSSD (root mean square of differences between adjacent R-R intervals), pNN50 (percentage of adjacent NN intervals that differ from each other by more than 50 ms).

Frequency analysis. Frequency domain HRV metrics complement time domain metrics including properties of oscillatory components in the heart rate dynamics. The power spectral density was estimated using the Welch's method. Three main spectral components commonly analyzed were the low frequencies (LF, sympathetic and parasympathetic activity) in the range of 0.04–0.15 Hz, the high frequencies (HF, parasympathetic activity) in the range of 0.15–0.4Hz and the LF/HF ratio.

Non-linear analysis. Complex and non-linear interactions are involved in the genesis of HRV to reflect the internal chaotic state. The most representative metrics included the PP (Poincare Plot), a graphical representation of the correlation between successive NN intervals. The analysis comprised of fitting an ellipse oriented according to the line-of-identity and computing the standard deviation of the points perpendicular to and along the line-of-identity, referred as SD1 (standard deviation of instantaneous R-R interval variability) and SD2 (standard deviation of continuous long-term R-R variability), respectively. DFA (Detrended fluctuation analysis) was also calculated using a self-similarity parameter that represents the short-term fluctuations (α1) and the long-term fluctuations (α2). The SampEn (Sample Entropy) measures the regularity and complexity of a time series. Low values are associated with pathological condition whereas high values are associated with a good health.

D. Experimentation

Psychological and physiological data are collected in four sessions: the day before the patrol leaves (baseline), two during the patrol (D20 and D50) and the last one, one month after the vacation following the exit from the survival environment (recovery time). The chronology of the baselines has been adapted to operational possibilities. As far as possible, each of the subjects kept the same morning or afternoon time slot.

TABLE I
RANDOMIZED DISTRIBUTION OF SUBJECTS INTO THREE GROUPS

Groupe A (n=10)	Groupe B (n=10)
Hearing	Vision
Interoception	Interoception
SPANE	SPANE
Stress (HRV)	Stress (HRV)

One participant was included in both groups.

Data collection the day before departure took place at the Ile Longue operational base from October 24 to 27, 2017. Each subject completed a series of questionnaires before the start of the mission. The SbQ was used to characterize our population. Mental health was assessed by the SPANE, sensory functioning by the SGI, and the interoceptive functioning by the MAIA. HRV was recorded as well as each of the extrasensors. All measures were repeated (except the SbQ) during the patrol and one month after the return. In order to minimize the experimental load for each of the participants and the time constraint for the doctor on board the SSBN, each subject was randomly divided into two groups (A, B) for the study of stress levels, mental health and sensory (Table I).

E. Data Analysis

Data analyses were performed using Python (Python, Software Foundation, Wilmington, v3.8) and RStudio (RStudio, Boston, v1.2 5001) software. For population description, comparisons between groups were performed using t-test for the quantitative data, or nonparametric Mann-Whitney analyses as they did not have a normal distribution. We categorized stress adaptability groups according to HRV metrics before the patrol linked to parasympathetic activity and chaotic internal state (RMSSD, pNN50, HF, SD1, SD2, α1, α2, SampEn). A principal component analysis (PCA) was then applied to eight HRV metrics to have the most meaningful components. A k-means, an unsupervised machine learning algorithm in Python, was applied to separate our population in terms of stress adaptability based on HRV profile at rest. Statistics were computed for all outcome measures using RStudio. The Shapiro-Wilk test was used to determine whether data were normally distributed. T-test was performed individually to explore the presence of significant differences in psychological functioning and the sensory abilities of submariners according to the HRV profile. For comparing the impact of the mission between groups, deltas were calculated for each variable. For the impact of the mission at the first part of the patrol, delta = Day20 - baseline. For the impact of the mission at the second part of the patrol, delta = D50 - baseline. For the recovery impact, delta = recovery-baseline. For all analyses, statistical significance was set at $p < 0.05$. Trends to a difference were considered when $0.05 < p < 0.1$.

IV. Results

A. Population Description

Out of 29 submariners recruited, ten dropped out during the experiment. 19 submariners, 29.73 years old (± 6.94) with an average weight of 75.78 (± 8.77), were included in the analyses. Among them, 15 (78.94%) are in couple, eight (42.10%) reported at least one major family stress event, and 11 (57.89%) reported none. Five (26.31%) reported a major work-related stress event, and 14 (73.68%) reported none. Out of 19 of them, 15 (78.94%) are non-smokers. 12 submariners (63.15%) have a morning chronotype (totally morning or rather morning) against seven (36.84%) with an evening chronotype (totally evening or rather evening). 18 submariners (94.73%) are right-handed, one did not declare his laterality. The average length of service is 7312 hours on SSBN (± 7151). Eight submariners (42.10%) are on « off-watch » rhythm, working in day shifts, without any night shift (except for unscheduled interventions), and 11 (57.89%) work on watch shift, meaning a daily night watch, alternating between 8:00 pm and midnight, then between midnight and 4:00 am, then between 4:00 am and 8:00 am on the third night [37].

B. HRV Profiles and Related Psychosensory Differences at Baseline

The eight HRV data recorded at rest were standardized by removing the mean and scaling to unit variance. The PCA yielded two components to reduce the large size of HRV metrics and subsequently used in a k-means. The results of the analysis are presented in Table II. The first factor which explained 69% of the variance, encompassed the temporal domain (RMSSD, pNN50) as well as SD1. The second factor explained 14% of the variance and encompassed indices of the nonlinear domain (SD2, α2, SampEn).

TABLE II
Loading Matrix for the PCA

Metrics [units]	Factor 1	Factor 2
RMSSD [ms]	**0.416**	0.130
pNN50 [%]	**0.415**	0.039
HF [ms^2]	0.383	0.186
SD1 [ms]	**0.416**	0.130
SD2 [ms]	0.324	**0.422**
α1	-0.373	0.358
α2	0.088	**-0.593**
SampEn	0.283	**-0.519**

Correlations between each HRV metric and the factors are shown. The analysis gave rise to two components.

The k-means characterizes two groups, differentiated on their physiological functioning (Fig. 1).

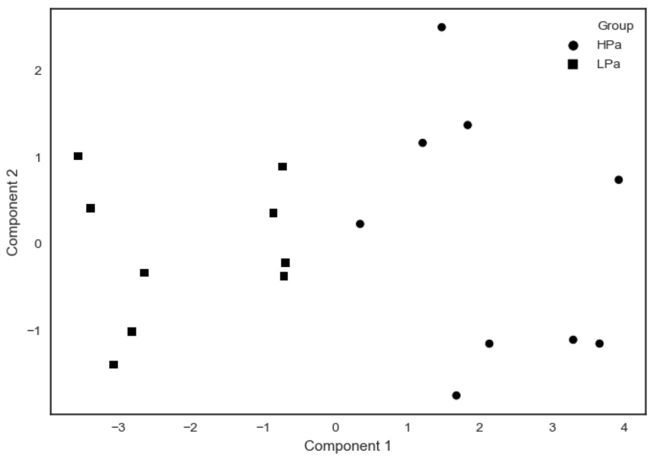

Fig. 1 k-means clustering analysis applied on PCA components based on HRV metrics

Table III describes physiological differences between groups. At baseline, the first group exhibited a high parasympathetic HRV functioning (HPa profile) characterized by a predominance of Parasympathetic Nervous System (PNS) activity at rest compared to second group (LPa profile). Results from analyses of the nonlinear domain follow this pattern. Subjects with the HPa profile exhibited a more adaptable HRV characteristics with greater unpredictability cardiac biosignal as evidenced by entropy and greater flexibility for a better return to homeostasis as reflected by the fractal analyses.

TABLE III
CHARACTERISTICS OF SUBMARINERS FOR EACH PROFILE (N = 19)

HRV metrics	LPa profile (n=10)	HPa profile (n=9)	*p-value*[*]
RMSSD	29.16 ± 10.17	62.55 ± 8.71	0.000
pNN50	9.67 ± 8.08	42.37 ± 7.76	0.000
HF	342.03 ± 293.55	1869.17 ± 679.98	0.000
SD1	20.62 ± 7.19	44.23 ± 6.15	0.000
SD2	75.06 ± 21.50	114.09 ± 24.46	0.002
α1	1.31 ± 0.12	0.98 ± 0.20	0.000
α2	0.96 ± 0.11	0.98 ± 0.14	0.75
SampEn	1.28 ± 0.14	1.54 ± 0.24	0.01

[*]*p-value* for analysis of unit cluster effect. Means differ at the p<0.05 level except for α2 by t-test. Median differs at the p<0.05 level for HF by Mann-Whitney.

No difference is observed on sociodemographic data, as well as on mental health and exteroceptive assessment between both groups (LPa vs. HPa profile). Specifically, no difference was observed between group for the number of reported stress life events. In sensory functioning (SGI), a significant group effect (t = 2.4083, df = 16.767, *p* = 0.02) for perceptual modulation showed a higher subscore for LPa group compared to HPa group. A significant group effect (t = 2.0561, df = 15.806, *p* = 0.05) for over inclusion showed a higher subscore for LPa group compared to HPa group. The tendency to a group effect (t = 1.9661, df = 13.263, *p* = 0.07) for distractibility suggests a higher subscore for the LPa group compared to HPa group. A tendency to a group effect (t = 2.0012, df = 15.557, *p* = 0.06) for fatigue stress modulation suggests a higher subscore for the LPa group compared to HPa group. In interoceptive functioning (MAIA), a significant group effect (t = -2.1827, df = 13.959, *p* = 0.04) for trusting subscore shows a lower trusting for the LPa group compared to HPa group.

C. Impact of LPa vs. HPa HRV Profile on Patrol Functioning

In interoceptive functioning (MAIA), there is a group effect (t = -2.5345, df = 16.506, *p* = 0.02) on the noticing delta (D20). The LPa group has decreased its score while the HPa group has increased its score. There is a significant group effect (t = -2.7722, df = 16.973, *p* = 0.01) for not distracting delta (D50). The LPa group has decreased its score whereas the HPa group did not change. In exteroceptive functioning, we only found differences for the hearing assessments. At delta D20, there is a tendency to a group effect (t = -2.0656, df = 6.5693, *p* = 0.08) at 2000 Hz only to the right ear. The LPa group would decrease its LDL while the HPa group would increase its LDL. At delta D50, significant group effects were observed at 1000 Hz (t = -2.2627, df = 7.9872, *p* = 0.05), at 2000 Hz (W = 4, *p* = 0.05) to the right ear. Tendencies to a group effect at 500 Hz (t = -1.9124, df = 7.2808, *p* = 0.09), at 8000 Hz (t = -2.0925, df = 7.1209, *p* = 0.07) were also found for the right ear. For each relevant frequency, the LPa group has decreased its LDL while the HPa group has increased (or tended to increase) its LDL. There is a significant group effect in HRV (W = 71, *p* = 0.03) for NNI mean delta (D50). The LPa group has increased its value while the HPa group has decreased its value. Significant group effects were observed for SDNN at both delta D20 (t = 2.5389, df = 16.505, *p* = 0.02) and D50 (t = 2.8346, df = 16.997, *p* = 0.01). The LPa group has increased its value while the HPa group has decreased its value. Significant group effects were observed for RMSSD at both delta D20 (t = 2.4566, df = 12.753, *p* = 0.02) and D50 (t = 3.2138, df = 14.573, *p* = 0.005). The LPa group has increased its value while the HPa group has decreased its value. Significant group effects were observed for pNN50 at both delta D20 (t = 2.199, df = 13.044, *p* = 0.04) and D50 (t = 3.0919, df = 13.781, *p* = 0.008). The LPa group has increased its value while the HPa group has decreased its value. Significant group effects were observed for LF at both delta D20 (t = 2.8258, df = 13.288, *p* = 0.01) and D50 (t = 3.6248, df = 16.282, *p* = 0.002). The LPa group has increased its power while the HPa group has decreased its power. Significant group effects were observed for SD1 at both delta D20 (t = 2.4568, df = 12.753, *p* = 0.02) and D50 (t = 3.2139, df = 14.573, *p* = 0.005). The LPa group has increased its value while the HPa group has decreased its value. Significant group effects were observed for SD2 at both delta D20 (t = 2.4513, df = 16.733, *p* = 0.02) and D50 (t = 2.7237, df = 16.948, *p* = 0.01). The LPa group has increased its value while the HPa group has decreased its value.

D. Impact of LPa vs. HPa HRV Profile on Recovery

In sensory functioning (SGI), there is a significant group effect (t = -2.0955, df = 14.962, *p* = 0.05) for fatigue stress modulation delta. The LPa group has decreased its score while the HPa group has increased its score. In interoceptive functioning (MAIA), we only found differences for four subscore dimensions. There are significant group effects for emo-awareness delta (t = -2.1498, df = 16.165, *p* = 0.04), self-regulation delta (t = -2.4773, df = 13.22, *p* = 0.02), and body listening delta (t = -3.7445, df = 14.14, *p* = 0.002). There is also a tendency to a group effect (t = -1.9755, df = 16.471, *p* = 0.06) for noticing delta. Whatever the dimension, the LPa group has decreased (or tended to decrease) its score while the HPa group has increased its score. We found significant group effect in HRV for pNN50 delta (t = 2.1892, df = 16.611, *p* = 0.04), RMMSD delta (W = 73, *p* = 0.02), HF delta (W = 75, *p* = 0.01), SD1 delta (W = 73, *p* = 0.02). The LPa group has increased its value while the HPa group has decreased its value. Tendencies to a group effect were also found for SDNN delta (W = 68, *p* = 0.06) and SD2 delta (t = 1.9775, df = 16.76, *p* = 0.06). Whatever the biocardiac variable, the LPa group has increased (tended to) its values while the HPa group has decreased them.

V. DISCUSSION

The aim of this exploratory study is to evaluate the impact of stress on mental health functioning and sensory degradation of submariners during a mission confined on SSBN by considering interindividual differences to stress adaptability. To this end, we have differentiated between two groups based on submariners' HRV profile at baseline. It is the first study to explore the characterization of stress adaptation profiles based on HRV metrics, using dimension reduction and unsupervised machine learning clustering algorithm. We identified a HPa group associated with more adaptable HRV characteristic (greater unpredictability and flexibility of cardiac biosignals), and a LPa group associated with less adaptable HRV characteristic (less unpredictability and flexibility of cardiac biosignals). These findings are coherent with the research work of the reciprocal connections between the heart and the brain [85]. The neurovisceral integration model developed in the work of Thayer describes the interconnections between the prefrontal cortex and cardiac activity [86], [87], [22]. This model postulates that parasympathetic activity serves as an indicator of the effectiveness of these interconnections [88], [89]. The authors assume that the higher the resting parasympathetic activity, the more capable the individual is of responding to environmental stimuli, and therefore the more adaptable they are [88]. Similarly, the biological functioning of the human organism is based on many reactions involving numerous central and peripheral structures, which are themselves activated on multiple time scales. A high level of complexity in neurophysiological systems allows young and healthy individuals to respond with significant flexibility and robustness to different environmental stimuli without disturbing their longer-term homeostasis [90], [91].

There is no difference on sociodemographic data, as well as, on psychological state between LPa and HPa HRV profile. On one hand, this absence of difference on sociodemographic, and psychological variables at baseline may reflect a healthy and rigorously selected population. The level of mindful functioning in this population is high compared to the general population [76]. Mindfulness, the ability to be fully present and conscious in the present moment, increases resilience to stress [92]. On the other hand, the two groups differ on sensory functioning. The HPa HRV profile exhibited higher sensorial functioning (higher confidence in their interoceptive body sensations trust and lower perceptive distortion levels) compared to the LPa HRV profile. Precisely, the LPa HRV profile would be more sensitive to modulation of stimulus intensity and perceptual flooding as well as to anomalies in focal attention with a tendency to radial attention difficulties resulting from a low perception threshold and vulnerability to perceptual and attentional anomalies during periods of fatigue and stress. This was associated with a lower confidence in their body sensations. The literature has highlighted the interception as a multidimensional construct and its involvement in emotional regulation [93]. The link between high HRV and interoceptive awareness abilities is increasingly established [94]. In accordance with the literature, the LPa HRV profile shows a less efficient sensory functioning at baseline. These findings are also consistent with those from Lafontaine [72] who reports interoceptive qualities in mindful submariners associated with a lower disposition to over-inclusion and distraction by external signals. There are in line with the neurovisceral integration model [86], [22] and the polyvagal theory [95]. They propose that the unconscious perception of the internal environment is modulated mainly by parasympathetic afferents. Our clustering also highlights the relationship between parasympathetic dominance and greater interactive awareness in the HPa HRV profile.

A. Impact of LPa vs. HPa HRV Profile on Patrol Functioning

The HPa group has a better awareness of body sensation whereas the LPa group decreases its ability to notice and focus on interoceptive stimuli between the first part of the patrol and the baseline. The LPa group tends to have difficulty for ignoring or distracting themselves from sensations of pain or discomfort while the HPa group remains at the same level between the second part of the patrol and the baseline. Interoception is considered as a complex process that includes objective process of neural coding, transduction, and central representation of internal stimuli [96]. The environment, a living space shaped by humans, is a vector of meaning and identity [97]. Its direct relationship with interoception underlines the quality of the internal use of the body and its sensations that regulate stress adaptations [98]. Several studies identified emotional stability/instability as a factor influencing adaptability in ICE [99]. These preliminary results suggest that the HPa group maintains an efficient sensory functioning during the patrol contrary to the LPa group. The impact of the patrol shows that auditory discomfort appears for lower sounds for the LPa group, contrary to the HPa group, which has a higher threshold of discomfort. These changes were observed over the whole frequency range, except around the conversational frequencies (3000-600 Hz), but only for the right ear. The SSBN in patrol is characterized by a high level of environmental noise. Whether such auditory environment may explain the observed changes in discomfort thresholds, results suggest that the HPa group would exhibit a more effective hearing adaptation compared to the LPa group. They highlight the enactive property of human with his environmental interactions. They suggest that neuroplasticity that leads to adaptation would be more effective for the HPa group. Neuroplasticity, the ability of the nervous system to adapt to environmental changes, is intrinsic to brain function and essential to its homeostasis. It characterizes all the processes of modification and subtle remodeling of the nervous system that are at work at any given time. The brain is therefore constantly learning, and the changes induced interact with our daily actions, intentions, and motivation. The lack of impact of the patrol on the submariners' vision would be explained by this neuroadaptation process. Van Ombergen et al. [100] have recently shown its involvement in analog environment during space flight. At least, they ask two questions: the absence of adaptation for the frequencies around 4000 Hz, and the laterality of the changes Main of our submariners are right-handed. Space mission research has shown greater hearing loss in the left ear than in the right ear in male astronauts [101]. It also appears that the left hemisphere is better able to filter out cross-noise than the right hemisphere and thus the right ear plays an important role in hearing processing [102], [103]. Listening responding to cross-sided lateralization could explain why right-handed people have higher LDLs. Further researches are needed for better understanding the mechanisms implying in adaptation and why this adaptation is right-sided.

During the mission, the LPa group increases cardiac variability. This has been associated with an increase in sympathetic activation. The HPa group exhibits opposite changes in HRV biosignals. The LPa group has a higher parasympathetic activation at D20 and D50, which can be explained by a quiet period of the mission after the intense training prior to departure in SSBN. This same group improves its internal state of complexity compared to inclusion. These results suggest that when the patrol is on, the mission becomes less challenging for this group. One hypothesis is that the baseline constitutes a stress period for the LPa group. Unfortunately, anticipatory anxiety was not assessed. Another framework for this result must be considered. Little [104] shows two interrelated categories of adaptive responses to environmental challenges. The first category of adaptation consists of short-term behavioral and physiological adjustments that are phenotypic responses to individuals' environmental challenges. Adaptation at this level includes individual coping mechanisms, behavioral, and biological adjustments to stress. However, these coping mechanisms are shaped by the second category of long-term adaptation. Long-term evolutionary changes (genotypic or cultural responses by groups of individuals or populations) would be expressed in terms of behavioral changes. Further, Weiss [79] emphasizes the role of temporal factors that challenge human adaptability. Then, the patrol challenges the short-term adaptation that appears to be more effective for the LPa HRV profile.

B. Impact of LPa vs. HPa HRV Profile on Recovery

At recovery, surprisingly, the LPa group is less subject to exacerbation of perceptual and attentional abnormalities by fatigue and stress. Recovery had a life-saving effect while the HPa group is more sensitive to sensory distortions during fatigue or stress. However, the HPa group recovered better in their ability to link emotional states, maintain, and control attention to body sensations, actively listen to the body for insight, notice and focus on interoceptive stimuli. The LPa group, one month after the end of the patrol, has still not recovered its interoceptive levels. These data suggest that stress adaptive submariners may have a reduced ability to discriminate body sensations. They question the impact of the patrol on the first stage of the interoceptive processing, which targets the perceptual and sensory level involving the perception of sensations and the ability to discern body cues in relation to the physiological and emotional state of the body [83]. Wohlwill [105] proposes that levels of adaptation would depend on the subject's prior experience. Consequently, adaptation levels allow for an individual's response to specific aspects of his or her environment as well as the overall level of stimulation it contains resulting from exposure to a given stimulus. The LPa group is marked by an active recovery from the deleterious impact of the patrol on their physiological functioning. A healthy subject is characterized by a more complex behavior associated with a neutral emotional valence [106]. Thus, the recovery had a beneficial effect on the most LPa submariners.

Contrary to our hypotheses, as during the patrol, the LPa group improves its HRV functioning in terms of parasympathetic level whereas the HPa group decreases it. However, this is associated with no change in terms of nonlinear domain, whatever the group. One possible explanation would be that the HPa group has a good quality parasympathetic brake, both through a good perception of its sensory information and through an overactivation of the Sympathetic Nervous System (SNS). Since the HRV LF metric reflects both SNP and SNS, measuring the functioning of the SNS would allow us to understand how it works. The HPa group would thus wear out throughout the patrol. Such a hypothesis needs to be evaluated using electrodermal activity (EDA) which is an objective marker of the dynamics of the stress response [107]. The tonic (i.e., slowly varying) and phasic (i.e., rapidly varying) components of EDA identify the excitation phenomenon and SNS activity, respectively. These components of EDA are under the influence of two neuroanatomical networks: the orbitofrontal, ventromedial prefrontal cortex (tonic component), and various areas of the brain (phasic component) such as the thalamus, hypothalamus, striated and extra-striated cortex, anterior cingulate and insular cortex, and certain lateral regions of the prefrontal cortex [108]. Other studies conducted during underwater patrols using HRV and EDA could be useful to better understand the relationship between the efficiency of the parasympathetic brake and the response to sympathetic stress.

C. Limits

This exploratory study has methodological shortcomings related to ecological conditions. First, the serious limitation of the present study is the small sample size. A study on such a population is complex both in terms of time constraints and access to infrastructure and personnel (operational constraints, attendance of participants). Moreover, the technical characteristics of the possible EDA systems do not currently allow their use on board an SSBN. Secondly, our results are not reproducible outside specific conditions and cannot be generalized. The SSBN is inherent to the ICE/EUE, characterized by a singular environment and in this context, to equipment of the French Navy. Thirdly, we are faced with an outstanding young and male crew, in excellent physical and mental condition due to a rigorous selection process. Fourthly, the psychological and interoceptive data collected through questionnaires are subjective measures. The use of intelligent sensors (i.e., Internet of Things) would allow a more objective recording of variables describing the subjects' psychological and physiological functioning.

VI. Conclusion

The clustering allows to separate two groups which adapt differently to the constraints of a patrol on SSBN. While these exploratory results need to be complemented by further studies (anticipatory anxiety evaluation and electrodermal activity), they are a first step to help develop effective countermeasures for submariners undergoing this degradation to maintain the submarine task force. These results can be used for other analogues in this environment such as research bases in Antarctica and future space missions. With the development of technology, human capabilities have expanded and made it possible for human beings to reside in extreme and unusual places that we could neither reach nor have survived in the past. Our study highlighted evidence of the benefits of a HPa profile against a LPa profile on psychosensory functioning during patrol and recovery. The goal would be to be able to predict the correct and thus least deleterious response to a patrol. The use of artificial intelligence represents an open door to predicting the maintenance of quality psychosensory functioning based on HRV. Advances in technology in recent years have led to relevant countermeasures via embodied virtual medicine, which should be targeted at PNS training, a guarantee of adaptability to stress and operational maintenance. These advances in our understanding of psycho-sensory adaptation in ICE/EUE bring us one step closer to our next journey to Mars.

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