Graduated Stress Exposure of Spaceflight Hazards in a Virtual Environment

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Graduated Stress Exposure of Spaceflight Hazards in a Virtual Environment

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Stress experienced by astronauts during high-level hazardous situations may poses risk to personnel wellbeing and to mission success. Stress inoculation training (SIT) provides individuals with experience of minor stressors and coping skills during non-critical times to enhance their resistance to stress. This study evaluates the effect of exposure to a low level stressor on physiological response and cognitive load in high level stressor setting. Simulation of fire emergency on the International Space Station (ISS) in a full-scale, immersive, interactive, 3D virtual reality environment facilitated a process for stress inoculation. The experimental settings included two groups that have been exposed to either virtual no-smoke or to virtual light-smoke conditions. The two groups then experienced a subsequent stress exposure in a later trail to heavy-smoke conditions. Physiological responses and cognitive load measure were collected during the trials. The results indicated weak differences in physiological responses between the two groups, in the heavy smoke conditions. Overall, no significant differences have been detected on cognitive load categories according to NASA TLX.

Nomenclature

ANS = Autonomic Nervous System
BPM = Beats Per Minute
CO = Carbon Monoxide
CSA-CP = Compound Specific Analyzer–Combustion Products
DBP = Diastolic Blood Pressure
EVA = Extra-Vehicular Activity
ECG = Electrocardiogram
HCl = Hydrogen Chloride
HCN = Hydrogen Cyanide
HF = High Frequency
HF n.u. = Normalized High Frequency
HR = Heart Rate
HRV = Heart Rate Variability
IVA = Intra-Vehicular Activity
ISS = International Space Station
LF = Low Frequency
LF n.u. = Normalized Low Frequency
LF/HF = index of cardiac parasympathetic activity
NASA = National Aeronautics and Space Administration
NIBP = Non-invasive Blood Pressure
**I. Introduction**

ASTRONAUTS can experience a number of in-flight life-threatening emergencies aboard the International Space Station (ISS), including decompression, fire, and toxic spills (e.g., ammonium leaks). Although these emergencies are rare, several incidents have occurred in space operations. On February 24, 1997, a Vika chemical oxygen generator malfunctioned aboard the Mir space station and caused a severe fire. Large amounts of toxic smoke filled the station for 45 minutes with near zero visibility. During a June 24, 1997 docking test of the Progress M-34 cargo vehicle, the M-34 collided with Mir causing decompression throughout the station and resulting in the need for permanently sealing the damaged Spektr module. On the ISS, astronauts have also experienced a number of false fire alarms, including a false ammonium alarm in 2014 that resulted in the crew temporarily moving to the Russian side of the station.

Not surprisingly, procedures training is of critical importance when preparing astronauts for the inherent risks in spaceflight. However, significant training challenges exist both on the ground as well as in space. Training astronauts requires a considerable amount of resources. And after training, it is often difficult to assess an astronaut’s ability to cope with the physiological and psychological stresses evoked by a life threatening situation.

Stress inoculation training (SIT) can potentially help astronauts build resilience to adverse experiences. As inoculation implies, SIT exposes individuals to minor stressors that can enhance resistance to stress. Stress arises in transactional situations where the individual’s perceived demands tax or exceed the perceived coping resources, which can result in physiological, psychological, behavioral, or social outcomes. From this transactional perspective, stress is a coupled relationship between the person and the environment. Therefore, psychosocial stressors cannot directly “cause” the stress response, but the extent to which they are stressful is a function of the individual’s cognitive appraisal of the situation. This coupling presents an avenue for SIT to train coping skills which prepare the individual to respond more favorably to negative stress events. Implementation of stress training can differ based on the nature of the stressor (e.g., acute or chronic) and the coping abilities of the individual. A main tenant of SIT, often called exposure training, is practicing stress coping skills over a series of sessions with gradually increasing levels of stressors until realistic stress levels have been achieved. Virtual reality simulations offer a practical venue to control stress levels and expose to astronauts to realistic scenarios.

Virtual reality simulations have been proposed as a potential training technique to help crew members prepare for emergency situations in space. NASA astronauts generally train for ISS emergency situations multiple venues, including a full scale ISS mock-up. Virtual environments have been used for astronaut ground-based personnel training for extravehicular activities (EVAs), T-38 flight simulations, and repair operations using the ISS Canadarm2 robotic arm. Assessments concluded that simulations had a positive impact on preparing space crews for the mission. However, VR simulations for intra-vehicular activity (IVA) have been used far less during training in lieu of full-scale mock-ups.

The objective of this paper is to present a prototype method for inoculating astronauts against the acute stress of a potentially life-threatening situation. In order to test this method, an experiment was performed wherein participants were to cope with the stress from a simulated fire aboard the ISS. The method relies on three main components: (1) task training, (2) exposure to graduated levels of stress to “inoculate” participants, and (3) a virtual reality environment (VRE) testbed for the fire scenes. A high-fidelity VRE utilizes less resources than traditional fire training and can provide highly controlled, gradually increasing levels of stress for inoculation. Furthermore, VRE can mimic aspects of microgravity that an earth-based simulation cannot (e.g., simulated smoke were buoyancy is not a factor).

The present study evaluated exposure to a low level stressor using a virtual reality simulation of an ISS emergency fire to gradually administer stress inoculation. In addition, this paper describes the development of a full-scale, 3D, interactive VR simulation of the International Space Station (SIMISS), and initial results from assessment of response to a fire scenario through implantation of procedures training.
II. Methodology

A. Participants
The sample was 20 male adults between the age range of 18-24 years. Participants were recruited from the Aerospace Engineering department at Iowa State University and have been randomly assigned to experimental groups (see below). None of the participants reported severe anxiety or high levels of stress during the experiments.

B. Experimental Design
The study implemented a 1 X 2 array, between subjects design. All participants were asked to follow a simplified ISS emergency fire response procedure in the SIMISS and locate the source of a smoke (Figure 1). During the simulation, a spontaneous source of smoke generated smoke in one of the modules aboard the ISS U.S. Orbital Segment (USOS). Participants were placed into 1 of 2 training conditions: (1) light-smoke exposure followed by heavy-smoke; and, (2) no-smoke exposure followed by heavy-smoke (described below). Participants experienced different virtual smoke and the corresponding atmospheric contaminant levels based upon the training protocol group they were assigned to (i.e., light-smoke or no-smoke). Virtual smoke and atmospheric contaminant levels rise as a function of time and distance from the fire source. Participants could evaluate contaminant levels using a hand-held joystick programmed to emulate the NASA-used Compound Specific Analyzer—Combustion Products (CSA-CP) device. The CSA-CP displays the virtual contaminant levels of carbon monoxide (CO), hydrogen chloride (HCl), and hydrogen cyanide (HCN) in parts per million (Figure 2). The purpose of the CSA-CP on board the ISS is to determine existence of a combusting fire, specifically dictating the point when Protective Breathing Apparatus (PBA) are required, and the proximity to the fire source.

The simulation followed the NASA ISS emergency fire procedures and gives instructions for crew responsibilities, location sampling (using the CSA-CP), and ISS system configuration. The simulation ended when participants either identified and reported the fireport label on the individual module rack which had the highest CSA-CP reading, or when the simulation smoke became condensed to a level where visibility was almost zero (~ 10 minutes from the beginning of the simulation).

C. Hypothesis
The working hypothesis is that participants first exposed to a light level smoke condition would experience reduced stress during a heavy-smoke condition in comparison to the group that first experienced the no-smoke condition.

D. Procedure
The experiment was divided into three separate sessions, each lasting approximately 60 minutes. All sessions were conducted at least 24 hours apart. In the first session, participants were trained on the ISS layout and modules, how to navigate using module labels (e.g., PORT=left side, STBD=right side), and how to identify key landmarks within the modules (e.g., treadmill, Cupola). The participants were then trained on the ISS fire procedures which included equipment, fireport rack labeling (e.g., JPM1F3), and proper procedure responses. A written test validated participants’ ability to navigate and perform the emergency fire procedure. A guided walkthrough in the SIMISS,
which included the ISS layout, navigation, landmarks and operation of the VRE were reiterated during the walkthrough.

In the second session, termed Trial 1, participants completed the procedures subject to either light-smoke or no-smoke. Just before both Trials 1 and 2, a brief review of the ISS layout and navigation was given. Participants were asked to remain seated and quiet for 10 minutes while baseline physiological data was collected. Both perceived workload and psychological data were collected after the session.

In the third session, or Trial 2, participants completed the same emergency response procedure as in Trial 1; however, in Trial 2 both groups were exposed to higher levels of virtual smoke and atmospheric contaminants (‘heavy-smoke conditions’ will be used to refer to these setting).

E. Independent Variables

The independent variable in the study is the level of smoke and contaminants in Trial 1. Participants either have been exposed to low level smoke and contaminants or have not been exposed in this trial.

F. Dependent Variables and Data Analysis

Data collected in the experiment includes autonomic stress responses and workload. The dependent variables are summarized in Table 1.

Autonomic Nervous System (ANS) responses— The ANS responses to stress were examined with two measures: heart rate variability and continuous non-invasive blood pressure (NIBP). Heart Rate Variability (HRV), which is the variation in time interval between heart beats, used electrocardiogram (ECG) recordings as a means of determining arousal. Electrodes were placed below the right clavicle above the coracoclavicular ligament (RA) and on the 6th rib near the mid-clavicular line (V4 lead) and a lower abdomen ground. ECG was sampled at 2048 Hz using Biopac MP150 hardware and recorded using AcqKnowledge software. Spectral analysis of HRV was performed using the Kubios HRV software. The raw data were first inspected visually for artifacts and corrected using low pass filters. Spectral density analysis of the HRV was used to parse the data into low-frequency (LF) (0.04–0.15 Hz) and high-frequency (HF) (0.15–0.4 Hz) bands. The very-low-frequency (VLF, <0.04 Hz) band was not included in this study because it is unreliable for short term recordings (<5 min). The LF and HF components were normalized to their total power in order to remove influences of VLF. LF/HF ratio was calculated to assess the sympathovagal balance, which is an index of the sympathetic activity relative to the parasympathetic activation. The HRV frequency bands for each participant were calculated in 60 second intervals over the duration of each trial. The first minute of the data were omitted to prevent anticipatory stress responses from skewing the assessments. Table 1 provides further details on the depended variables.

Table 1.
Description of dependent variable metrics, units, and frequencies.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Metric</th>
<th>Unit</th>
<th>Measurement Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autonomic stress response</td>
<td>Heart rate variability (HRV): LF/HF ratio, LF, LF n.u., HF, HF n.u., HR</td>
<td>ms², BPM</td>
<td>Before trial, throughout trials</td>
</tr>
<tr>
<td>Autonomic stress response</td>
<td>Systolic blood pressure (SBP), Diastolic blood pressure (DBP)</td>
<td>mmHg</td>
<td>Before trial, throughout trials</td>
</tr>
<tr>
<td>Workload</td>
<td>NASA Task Load Index (TLX)</td>
<td>Likert scale</td>
<td>Immediately post-trial</td>
</tr>
</tbody>
</table>

NIBP was used to assess systolic blood pressure (SBP) and diastolic blood pressure (DBP). A blood pressure finger cuff was placed on the participants’ non-dominant hand (FINAPRESS) and recorded using Biopac MP150 (1,024 Hz). Just before the trials, participants were asked to remain seated and quiet for 10 minutes while baseline data were collected. To calibrate the readings during baseline, an oscillometric blood pressure cuff was placed on the participant’s dominant upper arm and measured by a CNAP Monitor 500 at two different intervals during the baseline measurement. The raw data were inspected visually for artifacts and corrected using AcqKnowledge software. NIBP values were saved in 15 second interval samples. To give ample time for a resting state and preventing anticipatory...
stress interference, baseline BP data were calculated as the mean of the date from minutes 5 to 8 of the 10 minute baseline. The baseline was subtracted from the raw trial data to determine change scores. The first minute of the data was omitted to prevent anticipatory stress interference.

Workload—The NASA TLX was used to assess the difficulty of the task during exposure to the higher level of smoke density. A difference in workload could be interpreted as the workload contributing to a change in stress response and not primarily the environmental conditions of the emergency situation. The NASA TLX was administered immediately after the completion of a trial. NASA TLX participant scores were calculated based on a rating procedure.15

G. Testing environment
The research was conducted at the Virtual Reality Applications Center (VRAC) at Iowa State University. VRAC is home to the C6; the C6 is the world’s highest resolution virtual reality room. The facility is a 10 ft. x 10 ft. x 10 ft. cube in which all six screens have projected interactive stereoscopic images that provide total immersion in a virtual world. The C6 was used as a test-bed for initial development of these scenarios using NASA-provided models of the U.S. Orbital Segment (USOS) interior of the ISS (Figure 3).

Figure 3: Simulated ISS configuration. Russian segment of the ISS was not included in the simulation.

For all fire events crew members use CSA-CP to assess the atmospheric state. To emulate a CSA-CP, participants can call for a read out of the concentration of the gases through a vocal command or by pushing a button on a hand controller. Upon their command a floating window will appear with the atmospheric concentration values (Figure 2). The window will disappear after five seconds. The CSA-CP values are tied to a virtual smoke particle generator that is based on pre-defined equations for generation rate. Visual density of the virtual smoke and corresponding
concentrations of the toxic gases CO, HCN, and HCL increases with time and proximity distance from the source of the smoke according to Eq. (1-3), respectively. Using the ISS USOS maximum length ($D_{max}$) and varying the maximum and minimum levels of the gaseous compounds, the smoke and contaminant density could be set:

$$CO(t) = \left(\frac{CO_{max} - CO_{min}}{D_{max}}\right) \log \left(1 + \frac{9}{t_{max}}\right)$$  \hspace{1cm} (1)

$$HCl(t) = \left(\frac{HCl_{max} - HCl_{min}}{D_{max}}\right) \log \left(1 + \frac{9}{t_{max}}\right)$$ \hspace{1cm} (2)

$$HCN(t) = \left(\frac{HCN_{max} - HCN_{min}}{D_{max}}\right) \log \left(1 + \frac{9}{t_{max}}\right)$$ \hspace{1cm} (3)

The SIMISS includes fireport labels accurately placed on racks throughout the station. The labels have a unique code identifier which includes the module name, module surface, and rack number. For our simulation, the source of the smoke was set to be at fireport COL1A3_H2 in the Columbus module, close to the Harmony Node 2. The simulation starting position is the Node 1 module, since this is the closest “safe haven” to the Russian operations segment and the Soyuz escape capsule on the ISS.

H. Statistical analysis

Data analysis was performed using SPSS (23.0) software (SPSS, Chicago, IL, USA). For comparison of HRV components and NIBP, a linear mixed model with a first-order autoregressive model and random effect from participant sampling was used to calculate the fixed effect interaction of group and trial. Post-hoc analysis was performed through Bonferroni adjustments for multiple comparisons. Independent-samples t-tests (two-tailed) was used for the NASA TLX. Results were considered significantly different at the $p \leq 0.05$ level. All results shown are means ± standard error (SE).

III. Results

Comparison of baseline physiological measures between groups revealed no significant differences.

A. ANS Stress Response

The mean values for the HRV variables were within normal levels (Table 2). The normalized LF response suggested an increase in sympathetic modulation consequent to the heavy-smoke exposure that was weakly different by group (Figure 4; $F=3.366$, $p=0.072$). The response was greater in the no-smoke group. The decline in normalized HF with heavy-smoke exposure also weakly differed between the groups, being greater in the no-smoke group (Figure 5; $F=3.462$, $p=0.068$). The LF/HF responses also demonstrated potential trend for different responses due to the training protocol (Figure 6; $F=3.508$, $p=0.066$). Here, the no-smoke group displayed a higher LF/HF ratio than the light-smoke group during the heavy-smoke trial. While figure 7 indicate difference in DBP response between the two groups, statistical analysis provided no significant difference. Similarly, no significant difference was detected with SBP.

Table 2

<table>
<thead>
<tr>
<th></th>
<th>No-smoke</th>
<th>Light-smoke</th>
<th>P-value (group*trial)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 1</td>
</tr>
<tr>
<td>LF/HF</td>
<td>3.14 ± 0.47</td>
<td>4.47 ± 0.61</td>
<td>2.95 ± 0.35</td>
</tr>
<tr>
<td>LF (ms$^2$)</td>
<td>1301.19 ± 125.10</td>
<td>1268.15 ± 167.64</td>
<td>1150.67 ± 108.85</td>
</tr>
<tr>
<td>LF n.u.</td>
<td>63.48 ± 2.34</td>
<td>73.29 ± 2.0</td>
<td>62.13 ± 2.39</td>
</tr>
<tr>
<td>HF (ms$^2$)</td>
<td>751.71 ± 96.02</td>
<td>405.45 ± 47.68</td>
<td>665.96 ± 69.68</td>
</tr>
<tr>
<td>HF n.u.</td>
<td>36.38 ± 2.33</td>
<td>25.54 ± 1.98</td>
<td>37.62 ± 2.34</td>
</tr>
<tr>
<td>HR (BPM)</td>
<td>85.11 ± 1.60</td>
<td>86.47 ± 2.35</td>
<td>82.72 ± 1.47</td>
</tr>
<tr>
<td>SBP (mmHg)</td>
<td>25.15 ± 1.04</td>
<td>21.77 ± 1.28</td>
<td>26.40 ± 0.73</td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>10.95 ± 0.49</td>
<td>9.05 ± 0.80</td>
<td>11.13 ± 0.47</td>
</tr>
</tbody>
</table>
B. Workload

No significant differences between any of the TLX measures were found. However, Frustration during Trial 1 had a weak elevation ($F=4.921, p=0.104$), but then no difference during Trial 2 ($F=0.049, p=0.645$).

<table>
<thead>
<tr>
<th></th>
<th>No-smoke</th>
<th>Light-smoke</th>
<th>P-value (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental</td>
<td>52.9 ± 6.8</td>
<td>59.5 ± 6.4</td>
<td>0.487</td>
</tr>
<tr>
<td>Physical</td>
<td>23.3 ± 3.9</td>
<td>24.3 ± 3.9</td>
<td>0.864</td>
</tr>
<tr>
<td>Temporal</td>
<td>50.0 ± 9.5</td>
<td>48.6 ± 8.4</td>
<td>0.911</td>
</tr>
<tr>
<td>Performance</td>
<td>20.0 ± 2.0</td>
<td>28.1 ± 6.2</td>
<td>0.227</td>
</tr>
<tr>
<td>Effort</td>
<td>49.0 ± 6.5</td>
<td>61.4 ± 9.2</td>
<td>0.287</td>
</tr>
<tr>
<td>Frustration</td>
<td>21.0 ± 3.3</td>
<td>34.8 ± 7.2</td>
<td>0.104</td>
</tr>
<tr>
<td>Overall</td>
<td>36.0 ± 4.0</td>
<td>42.8 ± 5.1</td>
<td>0.313</td>
</tr>
</tbody>
</table>
Table 4
Two tails t-test analysis (mean ± S.E.) for NASA TLX (N = 20) after Trial 2

<table>
<thead>
<tr>
<th>Item</th>
<th>No-smoke</th>
<th>Light-smoke</th>
<th>P-value (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental</td>
<td>65.7 ± 8.5</td>
<td>67.1 ± 6.4</td>
<td>0.895</td>
</tr>
<tr>
<td>Physical</td>
<td>36.7 ± 6.3</td>
<td>34.8 ± 5.9</td>
<td>0.827</td>
</tr>
<tr>
<td>Temporal</td>
<td>70.0 ± 4.8</td>
<td>68.6 ± 9.0</td>
<td>0.890</td>
</tr>
<tr>
<td>Performance</td>
<td>27.6 ± 6.0</td>
<td>33.3 ± 8.4</td>
<td>0.588</td>
</tr>
<tr>
<td>Effort</td>
<td>60.5 ± 5.1</td>
<td>67.1 ± 8.2</td>
<td>0.500</td>
</tr>
<tr>
<td>Frustration</td>
<td>39.0 ± 8.9</td>
<td>44.8 ± 8.3</td>
<td>0.645</td>
</tr>
<tr>
<td>Overall</td>
<td>49.9 ± 4.0</td>
<td>52.6 ± 5.4</td>
<td>0.694</td>
</tr>
</tbody>
</table>

IV. Discussion
The results herein provide limited support that exposure training using a virtual environment may improve the stress responses to a heavy-smoke condition on the ISS. This finding is not supported by researchers Kenian and Freidland who found that graduated stress exposure is worse in comparison to low-constant intensity, high-constant intensity, and random-constant intensity.\(^\text{16,17}\) However, our results are partially supported by researchers Buamann, Gohm, Bonner that found that a single exposure to a stressful event reduced anxiety in a subsequent exposure.\(^\text{18}\)

A. Autonomic Stress Response
Compared to the group that was not initially exposed to a smoke condition (i.e., no-smoke), the group experiencing the light-smoke condition appeared to have an attenuated autonomic response to the more stressful heavy-smoke condition. The increase in LF, decline in HF and increase in LF/HF tended to be greater in the no-smoke group. Collectively, these data suggest that this group experienced greater autonomic arousal than the light-smoke group. The utility of HRV as a tool to assess the psychophysiological responses to stress is also reinforced. Here, HRV changed differently in the two groups, but neither HR nor BP did.

B. Workload
The trend of higher Frustration with the initial light-smoke exposure, compared to the no-smoke exposure, suggests the introduction of smoke may have changed the workload. However, during the heavy-smoke condition, the groups showed no difference between their perceived workload. Collectively, the TLX and HRV responses suggest that the simulated environment (i.e., the differing smoke conditions), and neither the workloads nor the procedures, were the primary source of stress for participants.

C. Limitations
While the results suggest a pattern in the stress response of the participants, the findings were not statistically significant. This can possibly be due to experiment design, experiment conditions, individual reactivity. In studies from Kenian and Friedland, they find that practice under stress can often interfere with task acquisition and lead to both poor performance and poor management of stress responses. The similar stress responses between our training groups could have been due to the stress of learning the emergency procedure. In the future, phased training would potentially solve this issue. The results could have also been impacted by the experiment smoke condition in Trial 1 being too low to cause a noticeable effect between light-smoke and no-smoke participants. Lastly, it is possible that some variance in the reactivity may have been cause by individual autonomic response to the type of task. Research utilizing different tasks could verify the robustness of this assertion.

V. Conclusion
The stress training protocol piloted in this experiment shows promise as a useful tool to elicit stress responses in users. Moreover, exposure training as used here also appears to have a positive effect on the responses seen during the stressful heavy-smoke condition. Future work is needed to study the further inoculation goal using stress training pedagogy for spaceflight applications.
References