Stress and Performance in Human-Robot Space Teleoperation Tasks

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***Abstract*—This paper investigates the relationship between stress, workload, and performance in robot teleoperation tasks. The investigation is motivated by the need to develop human-aware robot autonomy for space exploration. Based on prior work, the relationship between stress and performance follows an inverted-U, i.e. there exists an optimal level of stress where performance is maximized. We present a pilot study that utilizes real-time stress sensors on participants undergoing six rounds of stress-inducing or reducing conditions. The performance of the participants is recorded and analyzed with stress levels. We evaluate the relationship between stress (perceived and physiological), workload and performance across three teleoperation tasks. We find that the variation in stress is not significant across different rounds but do observe significance for perceived workload ($p < 0.001$), stress ($p < 0.05$), and respiration rate ($p < 0.01$) for a teleoperation task that requires continuous maneuvering to navigate the robotic arm through a maze. We propose an improved experimental design to better characterize the stress-performance relationship.**

***Index Terms*—Stress, workload, inverted-U hypothesis, teleoperation.**

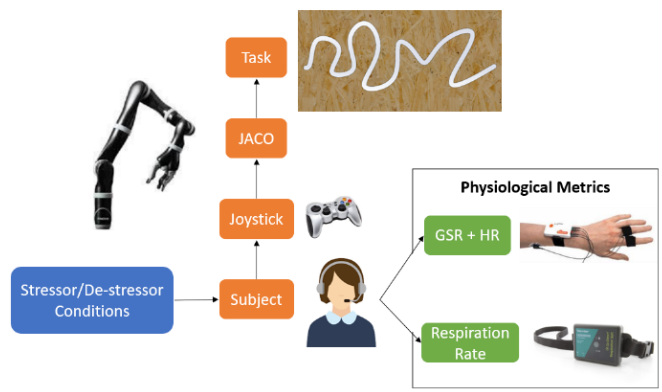


Fig. 1: Experiment setup.

I. Introduction

The 21st-century has seen a new era in spaceflight from the development of reusable rockets by SpaceX to NASA's ambitious plans to place a space station in the lunar orbit by the next decade [1]. With these technological advances comes the increased need for efficient and safe space assembly and orbit adjustment tasks. Space robot teleoperation is a powerful technique to fulfill this need where a human is given control over remote sensors and actuators [2]–[4]. A major factor contributing to the success of a teleoperation task would naturally be the human, or in the case of space teleoperation, the astronaut in control of the robot. Space is an unforgiving environment that does not tolerate human errors or technical failure [5]. High radiation, isolation and confinement, long distance from Earth, the lack of gravity in space can cause immense stress on astronauts [6]. Stress-performance relationship theorizing has its roots from the Yerkes-Dodson law [7] which states that there exists an inverted-U relationship between strength of stimulus and performance [8]. The inverted-U hypothesis states that there is an optimal level of stimulus for optimal performance. Increase or decrease from this optimal level will result in a drop in performance. We conduct a within-subjects user study to examine if there exists an ideal level of stress that can lead to optimal performance in teleoperation tasks.

In our pilot study, the participants must teleoperate a robotic arm to achieve a series of tasks of varying workload under different stressor conditions. It is important to note that stress and workload are correlated but distinct entities. Selye et al. define stress as "the nonspecific response of the body to any demand made upon it" [9]. Workload is defined as the ratio of resources available to achieve the task to the resources the human has available to dedicate to that task [10]. High workload or overload condition occurs when a large amount of resources are required to achieve the assigned task, but insufficient resources are available to be dedicated for the same. Underload or low workload condition occurs when there is low task demand and large resources available. Both overload and underload conditions can induce degradation in performance. By introducing different stress inducing and reducing conditions, we analyze the relationship between user's stress levels, perceived workload and performance on different teleoperation tasks. We measure both physiological stress through sensors and user's perceived stress through a survey. The performance of the users is determined by task-centric metrics as explained in Section IV B.

This work falls under the category of human-robot teaming. Human-robot teams require humans and robotic systems to communicate, coordinate and collaborate to perform a joint activity [11]. We note that this paper only covers a pilot study. The ultimate goal of this work is to create a controller capable of allocating tasks between the human operator and robot seamlessly. The controller would adjust the task allocation based on the ideal real-time state of the human operator which is determined from the first part of our work in this paper. These groupings are beneficial to both humans and robotic systems alike since each party has their limitations. Humans lack the ability to perform repetitive precise tasks while robots are unable to make intelligent decisions when faced with an unknown situation. This is especially true in space where there exist several unknown factors, making this work vital to progress in space exploration.

The contributions of this work are three-fold:

- We design a human-subjects experiment to investigate the inverted-U hypothesis in the teleoperation domain by incorporating various novel combinations of stress inducing or reducing conditions.
- We analyze the relationship between stress, workload and performance and find that performance is dependent on both perceived stress ($p = 0.048$) and physiological stress ($p = 0.001$) on tasks where the user must be constantly engaged while maneuvering the robotic arm.
- We propose an improved experiment design to study workload and stress in the teleoperation domain.

II. Background and Motivation

Astronauts work in highly stressful conditions that can adversely affect their performance. Astronauts are often assigned to work on robot teleoperation systems for performing maintenance tasks, moving supplies or grappling visiting vehicles on the International Space Station. In this work, we seek to investigate the relationship between stress and performance while executing teleoperation tasks. Prior works state that the relationship between stress and performance follows an inverted-U [8], [12]. The inverted-U hypothesis has been widely used by sport psychologists to understand the performance of athletes [13]. The hypothesis follows the Yerkes-Dodson Law, which examined the decision-making ability of mice under different stressor conditions [8].

The Yerkes-Dodson Law is a highly debated topic with papers arguing both for and against it. Teigen et al.stated that the law was intended to describe the relation between stimulus strength and habit-formation for tasks varying in discrimination difficulties, but have been generalized to represent the various versions of the inverted-U hypothesis [14]. While it is true that the law has often been misinterpreted over the years, some studies such as Arent and Landers' have shown that the inverted-U hypothesis holds true [15]. In this work, we wish to investigate the inverted-U hypothesis between stress and performance on teleoperation tasks.

This paper is also largely inspired by Johnson et al.'s work on a human-vehicle model designed to control mode transitions in a simulated human-in-the-loop lunar landing experiment based on the model's predictions of mental workload and situational awareness [16]. In a related paper, Johnson et al. review the issues, gaps and recommendations in dynamic task allocation in operational systems. A major drawback found in these systems is that the task re-allocation is reactive to changes in workload rather than proactive [17]. We aim to address this by using sensors to directly measure the state of the operator in real-time which would result in a system that is able to better allocate tasks before performance drops.

In our pilot study, we introduce stress inducing and stress reducing conditions inspired by prior work. Benham et al., used a mental arithmetic task as a stress inducing task and a hypnosis task as a stress reducing task [18]. Moorthy et al. also used a simple verbal mathematical task, but used other conditions such as background noise and time pressure as stress-inducing conditions. One of their conditions even combined all three conditions together. They found that all the stress-inducing conditions led to impaired dexterity and an increase in the incidence of errors [19]. Thus, we include mental arithmetic calculations and unpleasant background noise as our stress-inducing conditions. For the stress reducing conditions, we opted to use breathing exercise, meditation and music therapy. Pramanik et al. has shown in their study the immediate effect of a slow pace breathing exercise on blood pressure and heart rate [20]. Kaplan et al. and Astin's study shows stress reduction through mindfulness meditation to be an effective stress-reducing technique [21], [22]. Other studies used music therapy as a means of reducing stress levels in participants [23].

Moreover, we include surveys on spatial ability and personality to account for external factors that may influence the performance of subjects. The relationship between teleoperation and spatial ability has been widely studied. For instance, Eyal and Tenlick showed that the learning rates of novice users while using an angled laparoscope, a medical teleoperation device was strongly correlated with spatial ability [24].

To measure perceived workload on each task, we include the NASA TLX [25] and for perceived stress, we use the State-Trait Anxiety Inventory (STAI) [26]. Further, we also measure physiological stress using sensors to monitor galvanic skin response (GSR), heart rate (HR) and respiration rate. GSR sensors have been used in multiple studies and have shown to be an effective measure of stress [27], [28]. HR monitors have also been used in previous work to measure stress effectively [28]–[30]. We also monitor respiration rate as a supporting signal for a more robust measure as advised [30].

To the best of our knowledge, we are the first to test the inverted-U hypothesis in the teleoperation domain under varying stress conditions by conducting a human-subjects experiment. Understanding the relationship between stress and performance of human operators has potential applications in robot autonomy for space exploration. For instance, we can develop a human-aware controller that allocates tasks dynamically based on the stress level of the operator to ensure optimal performance. Further, by directly measuring operator state in the form of stress, we also address human variability in tolerance to workload.

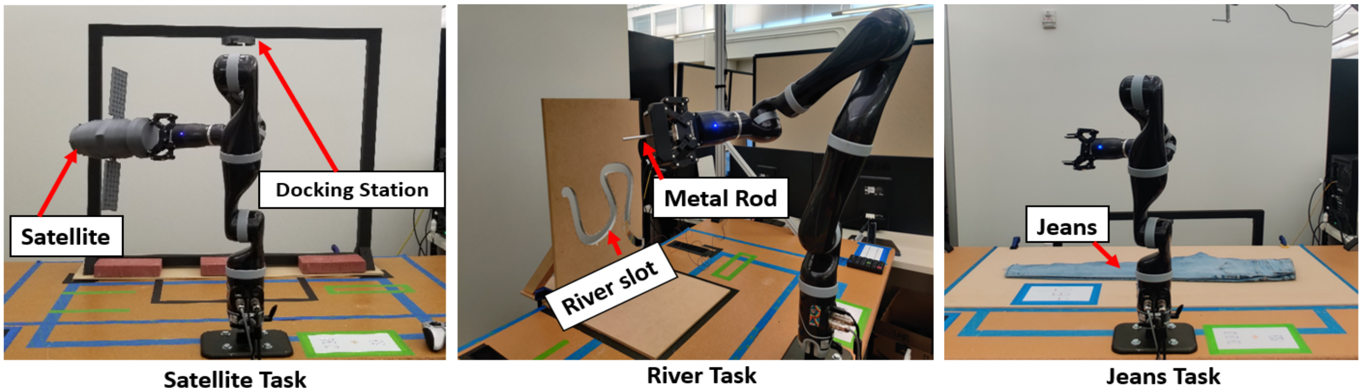


Fig. 2: Teleoperation tasks used in this experiment.

III. Experiment Design

We perform a three (tasks) × six (stressors) within-subjects experiment to understand the relationship between stress and performance in teleoperation tasks. The subjects are asked to complete three teleoperation tasks paired with two different stressor conditions each. The task-stressor combinations are sampled without replacement at random to form a total of six rounds. The subjects have five minutes to complete each round. At the start of every round, the experimenters instruct the participants to wear noise-cancelling (NC) headphones. Based on the stressor condition, appropriate auditory signals will be played via the headphones.

A. System Overview

1) KINOVA JACO Robotic Arm: For performing the teleoperation tasks, the participants must utilize the Kinova JACO arm mounted on a table as shown in Figure 2. The Kinova JACO is a seven degree-of-freedom robotic arm fitted with a Robotiq 2F-85 gripper as its end-effector.

2) Logitech F710 Gaming Console: The subjects are provided with a gaming console for teleoperating the robot.

3) Shimmer3 GSR+ unit: The Shimmer3 GSR+ is a wireless, wearable sensor that is used for Galvanic Skin Response (GSR) data acquisition. It is also equipped with an ear clip to monitor the heart rate (HR). The experimenter places this sensor unit on the subjects' non-dominant forearm to collect GSR and HR data from the user during the study.

4) Go Direct® Respiration Belt: The respiration belt uses a force sensor to monitor the respiration effort and rate. The experimenter places the belt around the chest of the subject to record their respiration rate while performing tasks in the study.

B. Study Conditions

1) Tasks: We designed three teleoperation tasks of varying difficulty to be completed under five minutes.

- *Satellite:* The satellite task involves the participants to use the JACO arm to dock a 3D-printed satellite model into its corresponding docking station attached to a wooden frame as shown on the left in Figure 2. Successful completion of this task requires careful alignment of the satellite with the docking station.
- *River:* In the river task, the participants must trace an aluminium-lined slot on a cardboard frame using a metal rod attached to the end-effector on the JACO arm as shown in Figure 2. The participants must insert the metal rod entirely into the frame and trace the slot carefully without touching the inner lining of the slot. If the rod makes contact with the slot, the buzzer will go off. Test for continuity between the metal rod and the slot is implemented via a buzzer attached to an Arduino board.
- *Jeans:* This task requires the participants to use the JACO arm to complete two folds on a pair of jeans attached to the table (See Figure 2). The fold lines are indicated with red tapes.

2) Stressors: While performing the teleoperation tasks, the subjects are exposed to various auditory stressors (stress inducers) and de-stressors (stress reducers) played through headphones. All de-stressor conditions (Breathing, Meditation, and Music) are performed prior to the start of the round, while the stressors (Siren, Siren+Math) are played concurrently while the subjects are performing the tasks. The subjects are seated in a separate cubicle and provided with an eye mask and NC headphones during the de-stressor conditions to ensure minimal disturbance.

- *Breathing:* Under this condition, the participants are asked to complete a ten minute guided breathing exercise prior to the start of the task.
- *Meditation:* The participants perform a five minute guided meditation session before the start of the round.
- *Music:* For this condition, the subjects listen to Symphony No. 6 Andante Molto Mosso by Beethoven for five minutes prior to the start of the task.
- *None:* No external stressors or destressors.
- *Siren:* A police siren of 80dB is played via the NC headphones while the participants perform the teleoperation task.
- *Siren+Math:* In this condition, the police siren is accompanied by random arithmetic questions played at unequal

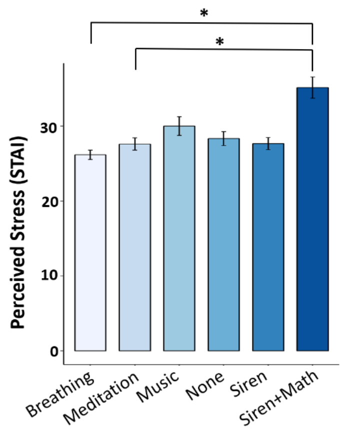


Fig. 3: Perceived Stress for the Satellite task.

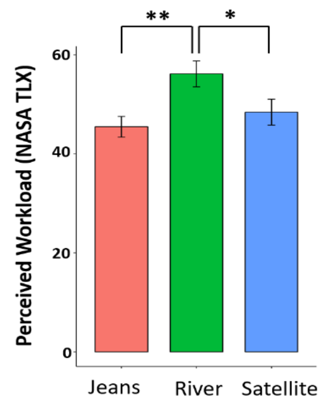


Fig. 4: Perceived Workload across three tasks.

intervals. Participants must answer these questions verbally and their answers are recorded by the experimenter.

C. Procedure

Prior to the start of the study, we obtained approval from the Institutional Review Board for human subject experimentation. We recruited 20 subjects (Male: 11, Female: 9) from the university campus whose ages ranged from 18 to 29 ($M = 22$, $SD = 3.38$). At the start of the study, the participants are asked to sign a consent form and complete the demographics survey. Upon completion, the base level sensor readings - HR, GSR and respiration rate of the subjects are recorded for two minutes. The experimenter then explains the controls of the gaming console and guides the subjects through a pick-and-place task. This is a practice task and the participants receive five minutes to familiarize themselves with the controls of the JACO arm. After the practice round, the subjects proceed to fill out the five factor personality test and a spatial ability test as part of pre-experiment surveys. Once the subjects finish the surveys, the experimenter instructs them to to perform six random task-stressor rounds. At the start of each round, the experimenter explains what the goal of the task is and shows a demonstration video on how to complete the task. The subjects have five minutes to complete each round. At the end of each round, the subjects are asked to fill out the NASA TLX [25] and STAI (State-Trait Anxiety Inventory) [26] surveys to monitor their perceived workload and stress levels. At the end of six rounds, the participants were de-briefed on the purpose of the study. All subjects were compensated with a $24 Amazon gift card for their participation in the study, which takes about two hours to complete.

IV. Preliminary Results and Discussion

In this section, we report the trends in stress, workload and performance across the three teleoperation tasks from our pilot study.

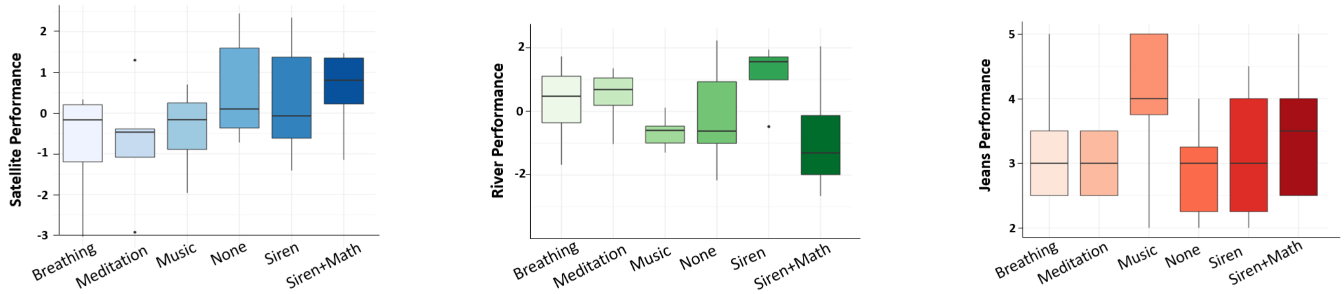
A. Trends in Perceived Stress and Workload

In order to estimate the perceived stress and workload for every task-stressor combination, the participants were asked to fill the STAI and NASA TLX surveys after each round. To analyze the factors on which perceived stress and workload is dependent on, we consider a linear mixed effects model, with either stress or workload as the dependent variable, and task type, stressor type, sensor values, task completion time, and prior experience working with robots. For the analysis of stress, we perform a repeated measures analysis of variance (ANOVA) and find that perceived stress is significantly dependent on skin conductance ($F(1, 120) = 6.676$, $p = 0.016$), task completion time ($F(1, 120) = 22.884$, $p < 0.001$) and previous experience controlling robots ($F(1, 120) = 5.848$, $p = 0.017$). The perceived stress across stressor conditions is found to be statistically significant only for the satellite task($F(5, 120) = 3.051$, $p = 0.012$). Post Hoc analysis for the satellite task using Tukey shows significant difference in stress between Siren+Math and Breathing ($p = 0.012$), and Siren+Math and Meditation ($p = 0.019$) (See Figure 3).

For the analysis of perceived workload, we resort to Friedman's test as the linear model fails the normality assumption. We find that workload is significant on the task type ($\chi^2 = 9.1248$, $p < 0.001$) but not on the stressor type. Post-Hoc analysis with Wilcoxon-Signed rank test shows significant difference in perceived workload between the river task and the satellite task ($p = 0.02$), and the river task and the jeans task ($p = 0.003$) (See Figure 4).

B. Relationship between Stress, Workload, and Performance

Since the three teleoperation tasks are very different from one another, we devised different performance metrics for each task. In this section we report the performance metric used and the factors affecting the subject's performance for every task. All statistical analyses reported in this section consider a linear mixed effects model with stressor type, perceived workload, perceived stress, user's prior experience with robots, scores from personality and spatial ability tests, change in respiration rate, skin conductance, and heart rate from the baseline readings as independent variables and the performance metric that we evaluate as the dependent variable.



(a) Satellite task (b) River task (c) Jeans task

Fig. 5: Performance versus stressors and de-stressors for the three tasks.

- *Satellite*: For the satellite task, we use the Euclidean distance between the desired goal position of the satellite and the final position of the satellite from the user's demonstration. To calculate the final performance metric, we normalize the Euclidean distance, and the task completion time and take the sum of both. The lower the value, the better the performance. On performing a repeated-measures ANOVA, we find that the performance on the satellite task is significantly dependent on the user's prior experience working with robots ($F(1, 40) = 5.691$, $p = 0.0219$).
- *River*: For the river task, we consider the contact time of the metal rod with the river slot while providing the demonstration, and the total time taken to complete the task. The two time factors are normalized individually and summed after inversion. The higher the value, the better the performance. On performing a repeated measures ANOVA with the river performance metric, we find that the performance on the river task is statistically significant on the user's perceived workload ($F(1, 40) = 28.748$, $p < 0.001$), perceived stress ($F(1, 40) = 4.139$, $p = 0.048$), and change in respiration rate from the baseline ($F(1, 40) = 11.542$, $p = 0.001$).
- *Jeans*: The performance metric for the jeans task is assessed by ratings on neatness and accuracy of folds on a scale of one to five by two evaluators anonymously.We use Cronbach's Alpha measure to verify the consistency of ratings between the evaluators ($\alpha = 0.9$). On performing a repeated measures ANOVA, we find that the performance on the jeans task is significantly dependent on the user's perceived workload ($F(1, 40) = 6.164$, $p = 0.017$)

V. Future Work

Upon analyzing the results from our pilot study, we find that we did not account for factors such as varied experience levels of subjects at the start of the study. Prior work suggests that inverted-U relationship is dynamic and may shift to the left or right based on experience [15], [31]. Further, we note that we did not account for the variations in subjective perceptions of workloads for different tasks under different stressor conditions, and inter-task learning effects. Thus, we propose some improvements to our pilot study. First, we wish to include a training element at the start of the study to obtain a more consistent expertise level among participants. To minimize the effect of expertise affecting performance, we propose to conduct a different pilot study to determine the duration and number of trials it takes for the participants' performance to plateau. We then allow our participants to first practice for the determined average number of trials from our pilot study. To diminish the task variation affecting the workload, we choose to keep our primary task constant for all the rounds. We choose the river task as our constant primary round because there exists a clear relationship between perceived workload and both physiological and perceived stress levels of the subjects.

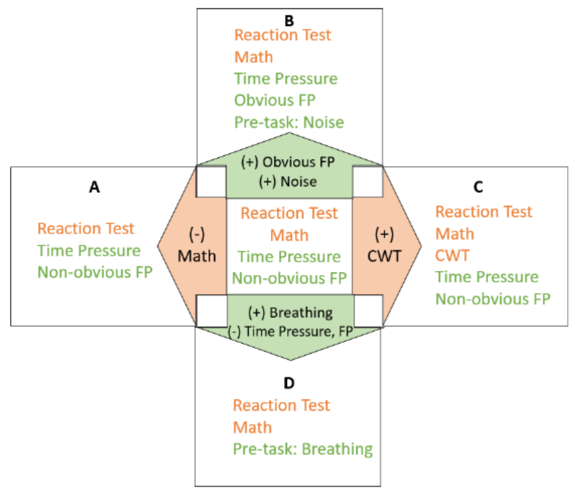


Fig. 6: Combination of conditions for each of the total five rounds in the stud., Orange represents the workload components and green represents the stress components. The center represents the nominal study conditions.

Previous research has often muddled the definition between workload and stress, causing confusion among the research community [9], [10], [18], [30]. To overcome this confusion, we will update our study to include separate workload and stress dimensions by clearly differentiating the types of conditions. The workload dimension consists of conditions that require participants to perform additional secondary tasks while the stress dimension consists of conditions that aim to distract and frustrate participants without the addition of extra labor. We modify our condition pool to include reaction time tests, verbal mental arithmetic and the stroop color word tests (CWT) [32] as workload conditions; and financial penalties (FP), time pressure, noise and breathing exercises as stress conditions. The conditions for each round are shown in Figure 6.

VI. Conclusion

We conduct a three (tasks) $\times$ six (stressors) within-subjects experiment to evaluate the relationship between stress, workload and performance in teleoperation tasks. We find significance between performance and stress (both perceived and physiological) for the river task. We speculate that the other teleoperation tasks were not as involved as the river task, and hence the individual's stress levels did not impact their performance significantly. This was also indicated by the user's perceived workload being significantly higher for the river task. Further, we propose an improved experiment design with the river task by considering variations in workload and stress along separate axes.

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