Towards a Serious Game based Human-Robot Framework for Fatigue Assessment

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ABSTRACT

Fatigue is a prevalent and important symptom in many diseases and disorders. It may be categorized into two main types physical and cognitive. It is important to study both of these as in the real world they frequently occur at the same time. In this paper, a testbed to study physical and cognitive fatigue is introduced. The system utilizes a game and a robotic arm to induce cognitive and physical fatigue respectively. The game incorporated the N-back tasks to induce cognitive fatigue. The robotic arm induced physical fatigue by resisting subjects' movements. Results indicate that this system is able to induce cognitive fatigue, and also indicate new directions for future research

CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**; **Empirical studies in HCI**; • **Applied computing → Health informatics**.

KEYWORDS

Robot-Assisted Training, User Skill Assessment, Cognitive assessment, Fatigue, Multi-Modal Dataset

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1 INTRODUCTION

Fatigue is one of the most common and prevalent phenomena in humans. It is an important factor in daily life. People who do manual labor, for example, assembly line workers, may be affected by fatigue due to repetitive manual labor. This may lead to physical fatigue affecting both their health and their ability to work. Due to the increase in demand for manufacturing, there may be extra pressure on the workers leading to an increase in cognitive fatigue. This fatigue is not just seen in manufacturing but in other fields as well. For example, an air traffic controller who has to maintain attention on multiple things continuously. Such fatigue may lead to a disastrous situation. Many workers handle heavy machinery and may also work with industrial robots. Fatigue may put them at risk of getting injured. Monitoring fatigue in the workplace is therefore needed to make the workplace safer and also to help the workers[15].

Fatigue is one of the most common symptoms in a multitude of diseases and disorders. Some of these include Multiple Sclerosis (MS), Traumatic Brain Injury (TBI), Parkinson's Disease (PD), among others [2, 10, 14]. It is prudent to monitor fatigue as a symptom of these diseases and disorders to study the progression of the disease and to study the efficiency of the drugs being administered. Apart from its medical necessity, monitoring fatigue can also give an indication of depression and quality of life of the patients [21]. In some cases, fatigue can also be responsible for the efficiency of the drugs administered.

Fatigue is a highly subjective and poorly understood phenomenon. There is no one definition of fatigue that is unanimously accepted. One definition by Jensen *et.al.* [11] defines fatigue to be caused by excessive physical or mental exertion. The most common way of measuring fatigue is to ask the subject to rate his/her fatigue using a survey. The questions asked are often highly subjective, for example, 'How tired do you feel now?' The nature of this survey makes it susceptible to human error and bias. This would be true for both the subjects and the examiner. Efforts to create a quantitative measure of fatigue through physiological and performance data are underway [7, 9, 18] but have historically proven difficult. Fatigue can be broadly classified into two types, physical and cognitive. Physical fatigue could be caused by overexertion of the body leading to fatigue in muscles/muscle groups or an overall sense of exhaustion [5, 23]. Cognitive fatigue may lead to a loss of cognitive control or a loss in high-level processing and attention [4]. It is important to study both types of fatigues coincidently for two reasons. The first is that in real-world scenarios a person may not just exert themselves physically or mentally, in many cases

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both would occur at the same time. The second is that physical and cognitive fatigue may interact with one another – an interaction which is not possible to study unless both are induced coincidently.

Studies have been done to assess fatigue through physical activity monitoring and through physiological sensing. Some studies have also looked at activities of daily living and wearable devices to asses fatigue [1, 6, 8, 16]. Physiological data like electrocardiogram (ECG), electroencephalogram (EEG) [3], and electromyogram (EMG) [19] among others have been leveraged to study fatigue.

In this paper, we present a testbed to study physical and cognitive fatigue at the same time. In this system, cognitive fatigue is induced using an N-back game which the participant played using a robotic arm. This system is the second version of our previous work where cognitive fatigue was induced using the Stroop effect [20]. The previous system allowed the user to move freely while providing no resistance. When the baseline test, conducted at the beginning of the experiment was compared with the baseline test conducted at the ending, it was found that even though cognitive fatigue increased, the performance did not suffer because of it. One explanation could be that the baseline test was not a good test to analyze fatigue. The main difference between our previous setup and the current setup is that in our previous setup Stroop test was used to induce cognitive fatigue and in this setup N-back task is used to induce cognitive fatigue. Multiple studies have used N-back task to induce this fatigue [24–26]. Thus employing this task may help study cognitive fatigue better. In the current system, we try to find if there is a relationship between the fatigue and the score in the more difficult game so that that can be used instead.

In this paper, we wanted to investigate whether the new system can indeed be used to study physical and cognitive fatigue at the same time. We also wanted to examine if we can find a relationship between fatigue and performance. This system will provide a unified set-up to study both physical and cognitive fatigue at the same time. Therefore, this will emulate real-world scenarios where both fatigues may occur coincidently.

2 METHODS AND MATERIALS

2.1 Setup

The system consists of two main components: the Barrett WAM arm and the game. The Barrett WAM arm is a 4-DOF (degree of freedom) robotic arm with a round end-effector. In this system, the arm is arranged in a joystick-like position where the users can hold the round end-effector with their dominant hand and move the arm to control a character on the screen (Figure 1). The arm resist the user's movements by controlling the torque on the joints of the arm. This forces the user to perform physical work while playing the game. The forces also ensure that the muscle is still worked after being fatigued.

This configuration of the arm is designed to act as an input device to a game displayed on the screen in front of the user. The game is designed as a 'dungeon crawler' game (Figure 2). Here the user is controlling a character trying to escape a maze. The character will spawn in the middle of a room that consists of four doors one on each side. The user has to escape the maze by selecting one of the four doors. They will do this by following the instruction given by a wizard character on the screen. Once they escape a room they will spawn in another room where they have to choose a door again. The instruction given by the wizard follows the N-Back condition [12] where if an instruction is the same as the instruction given n steps before the current step in a sequence, then the user must execute the instruction. For example, in the 1-Back condition, if an instruction is the same as the previous instruction, then the user must execute the instruction. Here the instructions provided are the directions of the door. The N-Back test is designed to provide a manipulation of working memory through increasing the number of items subjects must maintain. It has also been used to induced cognitive fatigue [24–26].

While the users are playing the game the system records physiological data. EEG, ECG, EMG, and Electrodermal Activity (EDA) are recorded from the users. EDA and ECG were recorded using Biosignalsplux, a physiological data collection unit designed by Biosignalsplux. ECG was recorded using the Lead II on the bipolar configuration of the Einthoven's triangle. EDA was recorded from the shoulders of the user. EMG was recorded from the triceps using Delsys Trigno Wireless EMG System. EEG was recorded using the MUSE headband. This headband is designed to sit comfortably on the forehead and records data from the frontal and temporal lobe using four electrodes. This paper studies the viability of such a setup to induce and study physical and cognitive fatigue. To this end, the relationship between the performance and subjective fatigue is studied. The physiological data collected by this system can be used to study the effect of fatigue under different conditions.

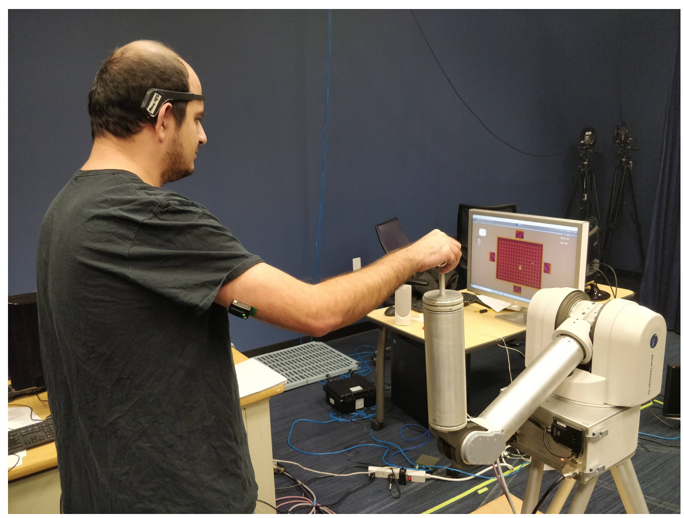

Figure 1: A user playing the game

2.2 Protocol

This study consists of three phases (Figure 3). In Phase 1, The users were asked to play the game during the 0-back condition. In this condition, the users would move to the door indicated by the wizard as soon as it was displayed. This is the baseline condition against which the other conditions were compared.

In Phase 2, we induced physical fatigue. Here we induced fatigue in the triceps. For this, the users were asked to perform an elbow

Figure 2: The game

extension exercise which utilizes the triceps. They were asked to sit on a chair with a dumbbell in their hand. They then moved the dumbbell by their side behind their back. They were asked to hold this position until they could not hold it anymore. They were provided with three options of dumbbells, five pounds, eight pounds, and ten pounds. They could select whichever they were comfortable with.

In Phase 3, the users were asked to play the game again but with the 2-back condition. Here the users moved in the direction instructed only if it matched the direction indicated two steps before. This is a more difficult condition than the 0-back, because it entails a larger cognitive load. Before users started the experiment, and after each experimental phase, users were asked to fill out a survey that assessed their physical and mental fatigue at that point.

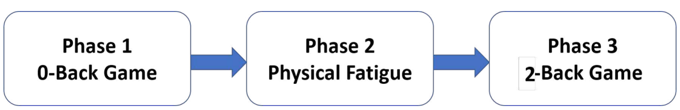

Figure 3: Experiment Protocol

3 DATA COLLECTION AND ANALYSIS

In this study, twenty participants were recruited. Of these twenty participants, there were seven females and thirteen males. The mean age of the participants was 24.5 ± 3.23 years. The participants were asked to perform the three phases of the study and fill out a survey before the first phase and after each phase.

The first survey was designed to collect demographic information and to gauge participant's current level of physical and cognitive fatigue as a baseline. The survey after each phase was designed to gauge their fatigue level due to the task performed. These surveys had five questions, 'How Tired do you feel?', 'Do you feel sleepy or drowsy?', 'Do you feel mentally fatigued?', 'Do you feel active and energetic?', and 'How difficult was the task?'. To quantify the responses, the participants were asked to respond on a Visual Analogue Scale (VAS). VAS is a common method to quantify qualitative parameters. This scale is a linear scale with one end being one extreme of the answer and the other end is the other extreme of the answer. For example in the question 'How Tired do you feel?', the answer would be between 'Not at all tired' and 'Extremely tired'. This scale can be designed for the desired resolution. In this study, the scale was quantified between one and ten with a resolution of one. To normalize the values for every participant, baseline was subtracted from the answers for each phase to get an indication of how these answers changed due to the phase.

The participants were asked to play the game in the first phase and the last phase. In both games the participant has one of two choices, choosing a door, and not moving. Participants could make a correct move in the game by either moving to the door indicated by the wizard (within the constraints of the current N-back condition) or by not moving (as determined by the current N-back condition). They could make an error by moving when they should have not moved, or by moving to the wrong door. To quantify their performance (score), each correct answer earned them one point while each wrong answer earned them zero points. For both games, there was a maximum of sixty-four instructions. This means that the maximum possible points that can be earned are sixty-four. This score was measured for further analysis.

This study investigates the participant's performance playing the different versions of the game and how that relates to their subjective feeling of fatigue. A paired T-test was performed on the participant's score while playing the two games. This was done to see if the level of cognitive difficulty affected their performance as previous studies have indicated that the difficulty increases with the increase in N in the N-back task [17]. As seen in Table 3, the test yielded a P-Value of $1 * 10^{-5}$. This indicates that there was a significant difference between the performance in the two games. As seen from Figure 4, the score for Phase 1 was greater than for Phase 3. To see if the change in difficulty of the game induced cognitive fatigue, a paired T-test was performed on the average responses for the mental fatigue question in the survey. As seen from Table 4, the test yielded a P-value of 0.002 indicating a significant difference and as seen from Figure 5 the value from Phase 3 was greater than Phase 1. To see if the survey responses significantly differed between the different phases, a repeated measure one way ANOVA test was performed. As seen from Table 5 only the question on difficulty yielded a significant difference in the ANOVA test. A pairwise comparison was performed on this result to check if there was a significant difference between each phase individually. The results indicated that the question of difficulty differed significantly between each phase. The question on whether they felt active differed between Phase 1 and Phase 3, and between Phase 2 and Phase 3. The question on whether they felt tired differed between Phase 2 and Phase 3.

To see if the participant's level of fatigue affected their performance, a correlation analysis was performed between the score in Phase 1 and Phase 3, and the survey results. Three types of correlation analyses were considered, Pearson's correlation, Kendall's τ, and Spearman's ρ. Of these, Pearson's correlation looks at the linear correlation between the two sets, while Kendall's τ and Spearman's ρ looks at rank-based correlation. Pearson's correlation assumes that the two sets were extracted from a normal distribution [22]. To confirm this a test of normality, Kolmogorov-Smirnov test, was conducted for the scores and the responses of the survey. In this test, the null hypothesis considered is that the set is extracted from

Table 1: Kendall Correlation between Survey Answers and Score

	Kendall			
	τ		P	
	0-back	2-back	0-back	2-back
Difficult	0.15	-0.12	0.47	0.52
Mental	-0.04	0.36*	0.88	0.04*
Tired	-0.04	0.18	0.88	0.33
Sleepy	-0.06	0.32	0.80	0.07
Active	-0.09	-0.05	0.69	0.81

* Significant

Table 2: Spearman Correlation between Survey Answers and Score

	Spearman			
	ρ		P	
	0-back	2-back	0-back	2-back
Difficult	0.17	-0.14	0.47	0.54
Mental	-0.05	0.44	0.83	0.05
Tired	-0.05	0.22	0.81	0.35
Sleepy	-0.07	0.40	0.77	0.08
Active	-0.10	-0.02	0.65	0.92

Table 3: Score Paired T-Test 0-back vs 2-back

Score	
0-back vs 2-back	$1 * 10^{-5}$*

* Significant

Table 4: Mental Fatigue Paired T-Test 0-back vs 2-back

Mental Fatigue	
0-back vs 2-back	0.002*

* Significant

a normal distribution, so if the P-value is less than 0.05 it would indicate that the set did not come from a normal distribution. Table 6 shows the results for the scores. As observed, the scores from neither phase were extracted from a normal distribution. Moreover, as observed in Table 7, only the question about if they felt active, in Phase 1, was extracted from a normal distribution. Therefore, Pearson's correlation was not used to evaluate the correlation between performance and subjective fatigue. Table 1 and Table 2 shows the result for Kendall's τ and Spearman's ρ. As seen from the tables only the question on mental fatigue showed a significant correlation with the scores in Phase 3 when evaluated with Kendall's τ.

4 DISCUSSION

This study investigated if the performance and subjective fatigue were affected by the different phases of the study. As seen from Table 3 and Table 4, the performance, and the cognitive fatigue were

Table 5: ANOVA and Multiple Comparison for Survey Results

	Tired	Sleepy	Active	Difficulty
ANOVA	0.14	0.22	0.45	0.005*
Phase 1 vs Phase 2	0.11	0.32	0.72	$7 * 10^{-4}$*
Phase 1 vs Phase 3	0.92	0.74	0.02	$1.58 * 10^{-5}$*
Phase 2 vs Phase 3	0.03*	0.30	0.008*	0.03*

* Significant

Table 6: Test For Normality: Score

	P-Value
0-Back	$4.72 * 10^{-19}$
2-Back	$4.72 * 10^{-19}$

Table 7: Test For Normality: Survey

Question	Phase 1	Phase 3
Difficult	$1.30 * 10^{-13}$	$3.25 * 10^{-18}$
Mental	0.04	$1.04 * 10^{-4}$
Tired	0.01	0.02
Sleepy	0.04	0.01
Active	0.13*	0.004

* Normal

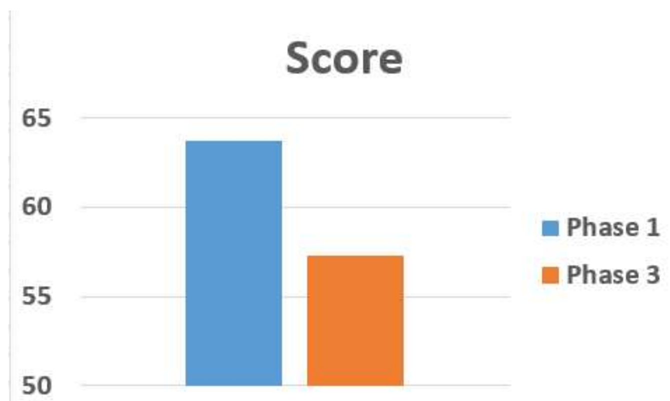

Figure 4: Mean Score for Phase 1 and Phase 3

indeed affected by the phases. In Phase 1 the participants played the 0-back game while in Phase 3 the participants played the 2-back game. N-back tasks have been proven to induce cognitive load in subjects [13]. Traditionally, N-back tasks are implemented using alphabets and a button that the subjects would press. In this study, a variation of the task was implemented where the participants were presented with directions instead of alphabets and had to perform physical work to play the game. By comparing the 0-back and the 2-back game in this study it was found that the method used in the study is in line with the traditional N-back task. One interesting thing to note is that the 2-back game, along with inducing cognitive load also increased cognitive fatigue, which is in line with the results

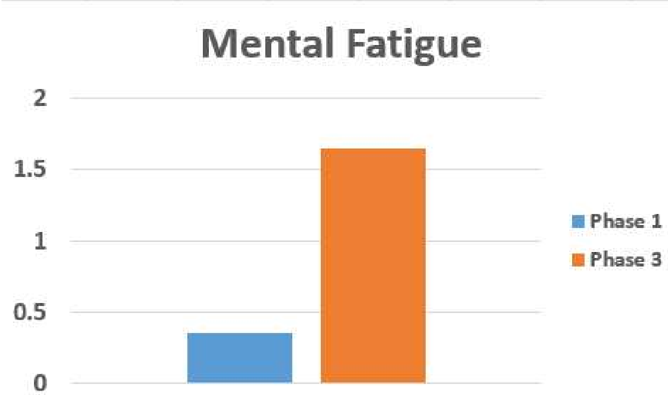

Figure 5: Mean Mental Fatigue for Phase 1 and Phase 3

of a study done on the relationship of cognitive fatigue and caudate which is an area in the brain using the 2-back task [24]. The study also looked at the differences in the other survey metrics between the phases. Unlike cognitive fatigue, the other metrics are important for all the phases. To analyze this, repeated-measures ANOVA with pairwise comparison was performed. As seen from Table 5 only a few metrics showed a statistical difference between the phases. The question on difficulty showed differences between all the pairs of phases and as observed in Figure 6 the result for this metric increases between each phase. This indicates that adding physical fatigue with cognitive fatigue may have affected their perception of the game. Although the tiredness did go down between Phase 2 and Phase 3, it is unclear whether this reduction happened during the tail end of the exercise or towards the beginning thus having no effect at all. The question of tiredness was designed to get an indication of physical fatigue. Therefore, it is interesting to see that, from the ANOVA, there is no difference between Phase 1 and Phase 2. Phase 2 was designed to induce physical fatigue and as observed in Figure 6, visually, there is an increase in the mean of the values between Phase 1 and Phase 2. One explanation may be that since there were only twenty participants in the study, the power of the test may have been low. Thus, to significantly prove no change in physical fatigue, more participants would be required.

The study also investigated the relationship between the performance and the subjective fatigue using the setup. To do this, a correlation analysis was performed between the performance and the survey results. As observed in Table 1 and Table 2 only mental fatigue and the score from the 2-back game had a significant analysis of the relationship as observed by Kendall's τ. For the other metrics, the analysis of the relationship was not significant. This, again, could be because there were only twenty participants in the study. A Significant correlation between mental fatigue and performance indicates that this method may be useful to study fatigue. Although, the fact that only Kendall's τ showed significant correlation indicates that further studies with a larger population may be required.

When correlation analysis was performed between tiredness and the score, it did not lead to a significant result. As mentioned above, one explanation could be because of the number of samples. Another explanation could be the type of fatigue that was induced. In this study, muscular fatigue was induced which is a peripheral fatigue. It could be possible that peripheral fatigue may not have enough effect on performance to study it using such a method. An investigation into central fatigue, which can be expressed as an overall sense of exhaustion, could lead to a better effect on performance. Lastly, metrics that weren't included in this study could have given us more insight into both cognitive and physical fatigue and thus may have lead to a better relationship.

These results show that the system was able to induce fatigue using the modified version of the N-Back task and the physical work. There, however, is a limitation to the design. The experimental protocol did not account for the order effect. Therefore, although, the mental fatigue increased and was correlated with the score, it is unclear whether the decrease in performance was just the result of mental fatigue or physical fatigue or a combination of both. Due to this, further studies with a different protocol are required.

5 FUTURE WORK

This paper provided preliminary work to prove whether the proposed system can provide a platform to study physical and cognitive fatigue at the same time. For this, the relationship between survey results and performance was studied. In the future, we would like to study more parameters from both performance and subjective fatigue. Furthermore, physiological data is collected in this framework to provide an opportunity to study fatigue using objective parameters. We would like to leverage these parameters in combination with the subjective parameters to study fatigue. In future studies, we would like to increase the number of participants thus improving the power of the statistical tests performed and we would also like to rearrange the phases to remove the order effect. Lastly, we would like to use this framework to study fatigue in different subjects like assembly line workers, post-stroke patients and people suffering from multiple sclerosis among others.

6 CONCLUSION

This paper designed and evaluated a system to study both physical and cognitive fatigue at the same time. Through the analysis, it was observed that there is a trend of change in the performance between the phases of the study. There is some indication of a relationship between the performance and the subjective fatigue but it is week. Through the analysis, it can be observed that the system shows potential for the use as a testbed to study physical fatigue and cognitive fatigue at the same time, although further analysis is required.

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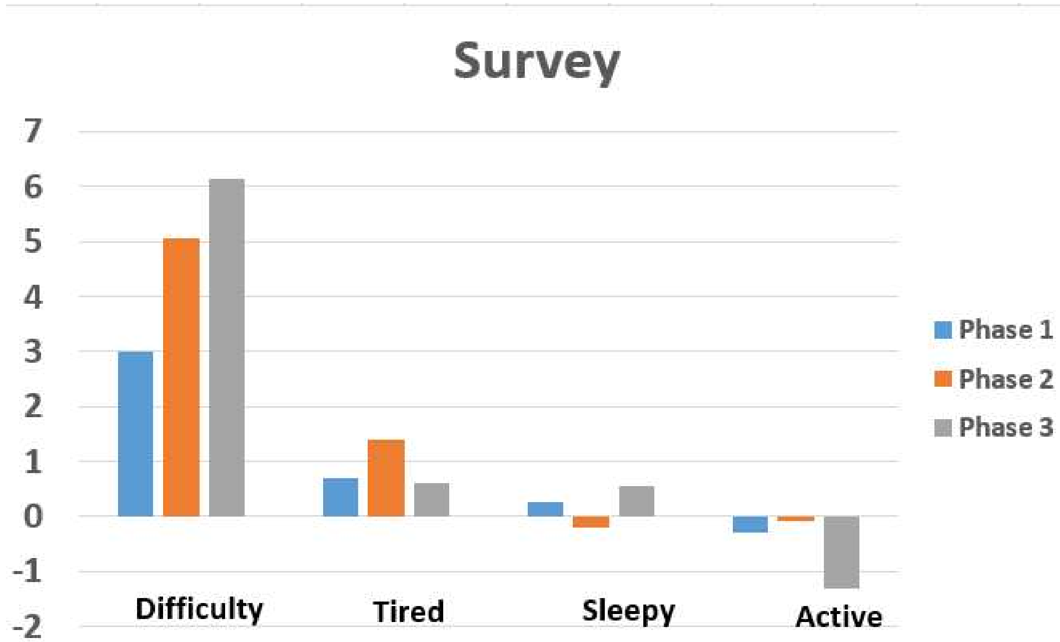

Figure 6: Mean Values for Survey

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