Brain signal analysis using EEG and Entropy to study the effect of physical and mental tasks on cognitive performance

Dineshen Chuckravanen
School of Life Sciences, Department of Sport and Exercise Sciences,
Northumbria University, Newcastle, NE1 8ST, United Kingdom
dineshen2013@gmail.com

Sujan Rajbhandari
Communications Engineering, University of Oxford, United Kingdom
sujan.rajbhandari@eng.ox.ac.uk

Andre Bester
Bester Labs, Newcastle Upon Tyne, United Kingdom
anb@besterlabs.com

Abstract:

Some theoretical control models posit that the fatigue which is developed during physical activity is not always peripheral and it is the brain which causes this feeling of fatigue. This fatigue develops due to a decrease of metabolic resources to and from the brain that modulates physical performance. Therefore, this research was conducted to find out if there was finite level of metabolic energy resources in the brain, by performing both mental and physical activities to exhaustion. It was found that there was an overflow of information during the exercise-involved experiment. The circular relationship between fatigue, cognitive performance and arousal state insinuates that one should apply more effort to maintain performance levels which would require more energy resources that eventually accelerates the development of fatigue. Thus, there appeared to be a limited amount of energy resources in the brain as shown by the cognitive performance of the participants.

Keywords: Attention, cognitive performance, EEG analysis, entropy analysis, mental fatigue

1. Introduction

Up to now, very little is known about the psychophysiological mechanisms that underlie mental fatigue and the cognitive functions [13]. Specifically within athletics, the ability to allocate and maintain attention during sporting competition can be as much taxing as the physical exertion associated with the sporting activity for successful performance [42]. However, minimal research has evolved in exploring cognitive fatigue as a possible performance mediator within athletics and hence, the influence of fatigue on attention and performance is still unclear. The studies that examined the impact of either acute or long-term exercise on cognition are equivocal, and it was suggested that physical exercise has a possible small positive effect on cognition [20]. Further studies are, therefore, needed to investigate the effects of exercise on cognitive performances [20, 50]. Based on the principle that processing in the brain is competitive, and it has finite metabolic resources, a new mechanistic explanation for the effect of exercise on the brain function, called the "transient hypofrontality hypothesis" was developed [16]. This hypothesis states that during physical exercise the extensive neural activation which is needed to run motor patterns, assimilate sensory inputs, and coordinate autonomic regulation causes a decrease in brain activity [16, 17].

In addition, the limitation of most studies related to the effect of exercise on cognition used only reaction time as the sole measure of cognition even in studies employing complex behavioural tasks [8]. Those relatively few studies [15, 44] that included response accuracy in their analysis, reported that there was either no change or increased accuracy with exercise. Therefore, by conducting this cognitive fatigue study, it was hoped to observe the response of cortical activities to an exhausting physical exercise, and how physical activity affects cognitive performance in terms of reaction time and accuracy as they seemed to reflect important aspects of cognition. The next section describes the methodology used to conduct this experimental case study.

2. Methodology

2.1 Participants Details

This research study was approved by the Ethics Committee of the School of Life sciences, Northumbria University at Newcastle. Twelve healthy and right-handed participants (6 males and 6 females) were recruited and their mean (± standard deviation) height was 1.73 (±0.08) m. The participants' age ranged from 25.9 to 33.3 years, and their body mass ranged from 56.6 kg to 82.8 kg. All the participants came to the neurophysiology laboratory on three separate occasions with at least one week apart so as to reduce any learning effect [32, 55]. In addition, these volunteers were moderately to highly mentally and physically active as they were required to complete a series of cognitive tasks lasting for half an hour on two occasions, and also on one occasion they had to cycle as hard as they could for about half an hour or until they felt they could not continue this physical activity anymore.

2.2 Description of the cognitive tasks

The rapid visual information processing (RVIP) and modified stroop (MST) tasks were used in this research study, and the psychological strain which was placed by these tasks on the participants was mostly cognitive [6, 12]. Hence, they needed to sustain attention for half an hour for them to be accurate and quick in their responses during the cognitive trials. For the modified stroop task (MST), the participants had to respond to the colour of the word appearing at the centre of a computer screen (Red, Blue, Yellow and Green) by pressing respectively and quickly the numerical keys (1, 2, 8 and 9) on the keyboard. Moreover, if the word that appeared on the screen was written in grey, they were required to respond to the word. For instance, if the word YELLOW was written in grey colour, then the participants would need to press the numerical key '8' which was associated to yellow colour. In addition, during the modified stroop task, they had to count mentally the number of white squares (size of 9 cm by 9 cm) and white circles (diameter size was 9 cm) that appeared randomly and sparsely at the centre of the screen. The duration of this type of cognitive task was 5 minutes. As for the rapid visual information processing (RVIP) task, the participants were required to respond to a specific sequence (odd or even) of integer numbers from 0 to 9 which appeared one at a time every 600 ms on the computer screen. For example, when they noticed three consecutive odd numbers (e.g. 3, 5, 7) or three consecutive even numbers (e.g. 2, 8, 6), they had to press the 'spacebar' on the keyboard as quickly and accurately as they could. The duration of this cognitive task was also 5 minutes. And then, these cognitive tasks were alternately presented to the participants for a period of 30 minutes so that there were in all three RVIPs and three MSTs which represented the cognitive battery test.

2.3 Hardware and software resources

The material resources that were used for this study comprised of Research Powerlab, and Octal Bio Amp systems (Powerlab, ADInstruments, Australia) for the recording of the electroencephalogram (EEG) data. The electro-caps (the electro-cap size can be small, medium or large) consist of Ag/AgCl electrodes embedded in the elastic electro-cap fabric to record EEG activities from the scalp, and these data was transmitted to the powerlab systems via an electro-cap interface (Electro-Cap International, Inc., USA). Moreover, the ECI electro-gel was used to reduce the resistance between the EEG electrodes and the scalp, and a digital multimeter (Draper 52320, UK) was used to measure this impedance. In addition, a '0-volt' potential 8-lines cable was used as a reference baseline voltage to measure the EEG potentials. Couple with that, a parallel communication interface port was used to send 8-bit parallel data from the Research Powerlab to the installed E-Prime software workstation. This communication interface was used to send 8-bit data to 'timestamp' the responses of the participants while responding to the visual stimuli on the computer screen. These 8-bit data actually represented 2-digit numbers called digital bytes that were assigned 'comment texts' (i.e. blue, red, green, yellow, square, circle, odd and even) to display on the real-time brain signal data upon the trigger of the corresponding visual stimuli. These would help to convert the continuous EEG data into data epochs time locked to specified event types for analysis purposes. Finally, the software that were used in this experimental case study were Chart 5 for Windows (Research Powerlab) to record and process the physiological signals, the E-Prime software version 2.0 to implement and conduct the mental fatigue tasks, and Matlab software 7.0 for data analysis.

2.4 Study protocol and procedures

On the first visit to the physiology laboratory, the participants completed each a screening health questionnaire to determine their eligibility for taking part in this research study and then, they were each assigned an identification number to protect their anonymity. The right size electro cap was identified using the electro-cap head tape measure (Electro-Cap International, Inc., USA) for each participant, and then they were given each a practice session on the cognitive tasks that they would need to complete during their second and third visits. Moreover, this first visit allowed the participants to familiarise themselves with the laboratory environment and the procedures.

During the second visit (also named the 'control' experiment), the participants completed first the Multidimensional Fatigue Inventory (MFI-20) questionnaire which comprised of 20 items assessing the general fatigue, physical fatigue, mental fatigue, reduced activity and reduced motivation. Before starting the cognitive battery test, the participants sat comfortably facing the computer monitor at a distance of about 60 cm [10] and the appropriate EEG electro-cap was fitted onto the participant's scalp according to the manufacturer's instructions (Electro-Cap International Inc., USA). Next, a blunted needle was used to fill each electro-cap electrode, relevant to this study, with the ECI electro-gel to ensure the impedance between the EEG electrode and the scalp was less than 5000 Ω using the digital multimeter. Then, EEG activities at the frontal midline (Fz), central midline (Cz), and parietal midline (Pz) were recorded while the reference Ag/AgCl electrodes were attached to A1 representing the left ear lobe [51], and the ground electrode was located at AFz representing the Anterior Frontal of the scalp [3]. The sampling frequency was set at 400 Hz which was sufficient to capture the EEG activities based on Nyquist's criterion [47].

Then, after each 5 min-block of cognitive task (either RVIP or MST), they had to complete the visual analogue scales (VAS) so that their mental fatigue, physical fatigue and concentration were quickly and easily monitored during the trial. For these visual analogue scales, the participants were required to mark in-between the horizontal scales that consisted of two extreme marks '0' and '10' representing low and high respectively. Afterwards, at the end of the cognitive experiment, they had to fill again the MFI-20 questionnaire to compare any changes in the subjective feeling measures between pre and post the cognitive battery experiment. As a preliminary procedure, a pilot study was conducted to test the reliability of the MFI questionnaire items using Cronbach's alpha [14, 45]. The value of the Cronbach's alpha was found to be 0.82 which showed a reliable tool for assessing the internal consistency of a psychometric test in representing subjectively the fatigue felt by these participants for this type of cognitive experiment [14, 45].

On their third visit (also named as the 'exercise' experiment), the participants each performed, first of all, an exhausting cycling exercise bout for about half an hour. They wore comfortable clothes and footwear to perform this tiring cycling bout on the Velotron (VelotronPRO, RacerMate Inc., USA) whereby they were instructed to cycle as hard as they could till they could not continue this physical activity anymore. After completing this physical activity, they had to complete the MFI-20 questionnaire, and then, during the cognitive trial, they were asked to complete the series of RVIP and Modified Stroop tasks similar to the second visit, while EEG data were recorded following the same procedure as described for the second visit. Finally, after completing the cognitive battery test, they filled again the MFI-20 questionnaire. As precautions, the participants were requested to try not to blink while responding to the visual cues, during the cognitive experiments, to reduce interference of the electrooculogram activities [19] to the measured EEG signals. Apart from the visual cues on the screen, there were neither other visual stimuli nor auditory stimuli that would distract the participants from the cognitive trials.

2.5 Data analysis

EEG activities were recorded while the participants performed the series of cognitive tasks in both experimental conditions (control and exercise). The following subsections explain in more details the recording and analysis of the EEG activities as well as the event related potentials (ERP) data.

2.5.1 EEG analysis

EEG activities were recorded continuously from the midline placements Fz, Cz and Pz according to the international 10-20 system electrode placement using the Ag/AgCl electrodes embedded in the elastic electro cap fabric (Figure 1). The cortical EEG activities were amplified, digitized, sampled at a frequency rate of 400Hz, and online filtered using a pass band of 0.1 to 100Hz using the powerlab systems [33]. Then, the EEG signals were digitally low pass filtered with a cut-off frequency of 30 Hz, and online reduced to a sample frequency of 100 Hz to analyse the EEG frequency bands of interest [3]. Moreover, artefacts such as blinking and fast eye movements were removed from the recorded signals based on any amplitude greater than ±70 μV [26]. Then, these processed signals were used for the EEG analysis.

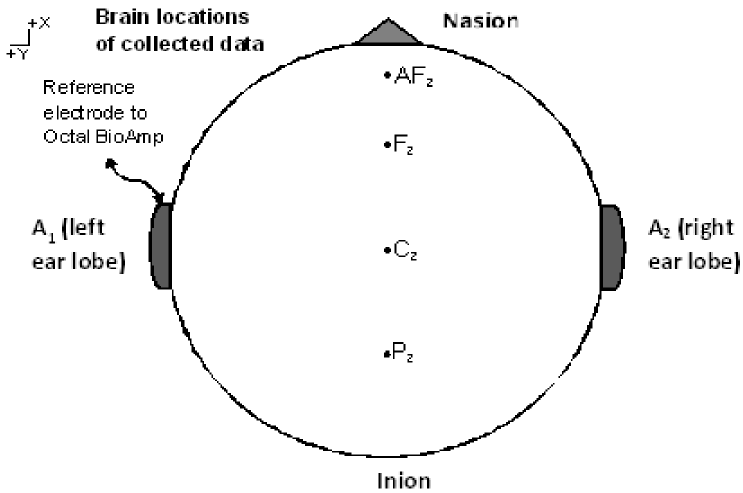

Figure 1. The 10-20 international system electrode placement showing the EEG electrode placement, the reference electrode (A1 - left earlobe) and the ground electrode (AFz), Fz (Frontal midline electrode), Cz (central midline electrode) and Pz (parietal midline electrode).

For the EEG analysis, the average power in the theta band (4 – 8 Hz), and alpha band (8 – 12 Hz) were computed at the frontal and parietal electrodes Fz and Pz respectively. Next, the ratio of these two powers was determined, and named the 'cognitive ratio' as several researchers found that the fronto-parietal network play important roles in cognitive activities [2, 9, 22].

2.5.2 Entropy analysis

Moreover, the entropy (i.e. the amount of information flow or content) of the EEG signals (Fz, Cz and Pz) were computed using Matlab software to represent an additional mathematical measure to compare the cognitive performance of the participants for each experimental condition (i.e. control vs. exercise cognitive trials). The entropy of a signal is becoming an emerging and promising mathematical method, especially in current clinical context, in quantifying the amount of information flow especially in the electroencephalogram (EEG) signals using both the degree of spatial and temporal integration of neuronal activity in the brain [5]. The mathematical principle of entropy is described as follows.

The information entropy was initially developed to measure and evaluate the information content of a transmitted communication signal [47]. Therefore, the entropy (H) is defined as the average amount of information per source output and is expressed by following equation:

$$H = - \sum p_i \log_2 p_i \text{ (bits/source output)} \quad (1)$$

Where p_i represents the probability of occurrence of the i^{th} output, log_2 is the logarithm function to base 2, and the summation (∑) of all the probabilities is equal to 1. From the entropy measures together with the EEG analysis, it was hoped to be able to observe any changes or associations in the brain activities with cognitive performance.

2.6 Statistical analysis

Firstly, all recorded and computed data were tested for normality using Kolmogorov-Smirnov (K-S) test [21, 31]. Then, a two-way factorial ANOVA (Analysis of Variance) was used to investigate the effects of time (6 intervals of 5 minutes) on various variables (e.g. reaction time, accuracy, cognitive ratio, heart rate, RR-interval and subjective measures of fatigue) for two experimental conditions (control and exercise) for same group of participants. When the main analysis indicated a significant interaction ($p < 0.05$) between the factors, follow-up analysis were achieved, adjusting error rates according to Bonferroni correction [4]. Furthermore, paired t-test was used to compare the means of any dependent variable subjected to these two experimental conditions.

3. Results

The results are divided into several sections that are namely the subjective measures that consisted of the visual analogue scales (mental fatigue, physical fatigue and concentration) and the MFI-20 questionnaire that assessed the general fatigue, physical fatigue, mental fatigue, reduced motivation, reduced activity pre and post the cognitive battery test; the cognitive performance of the participants in terms of both reaction time and percentage accuracy of responses to visual cues followed by the EEG and Entropy analysis.

3.1 Subjective measures of fatigue

A two-way (2 experimental conditions x 6 time intervals) factorial ANOVA with repeated measures was conducted on the visual analogue scale data to determine whether there was a statistical significance in the means of dependent variables that were mental fatigue, physical fatigue and concentration between the two experimental conditions (control vs. exercise) but on the same group of individuals. The within-subject variable was the time-on-task repeated measures that were denoted as time5, time10, time15, time20, time25, and time30 (i.e. time5 means 5 minutes of the cognitive task had elapsed, time10 means 10 minutes of the cognitive task had elapsed, and so on till completion of the cognitive task). The model assumptions in terms of normality using Kolgomorov-Smirnov (K-S) test [21, 31] and homogeneity of covariance using Box's test [1, 46] were evaluated and met in this statistical analysis. Furthermore, the MFI-20 subjective measures were analysed using a 2 (two experimental conditions) x 2 (pre and post cognitive tasks) factorial ANOVA with repeated measures, and the statistical results of these subjective measures of fatigue are as follows in the subsequent subsections.

3.1.1 Visual analogue scales (VAS) subjective measures

As shown in Figure 2, it was found that there was a statistically significant interaction in the percentage of mental fatigue between the condition type and time-on-task factor times ($F(6, 22) = 492.19$, $p < 0.001$) as well as there was a significant main effect of time-on-task (time5 to time30) ($F(5, 22) = 463.794$, $p < 0.001$). In addition, there was also a significant main effect in the condition type (F (1, 22) = 713.133, $p < 0.001$) which represented a large effect size. For the physical fatigue subjective measure, there was a significant difference between the two experimental conditions ($p < 0.001$), and within the subject test times ($p < 0.001$). However, there was no significant difference between the means of the concentration visual analogue scale for these two experimental conditions ($p = 0.057$) despite a significant difference ($p < 0.001$) in the time-on-task repeated measures.

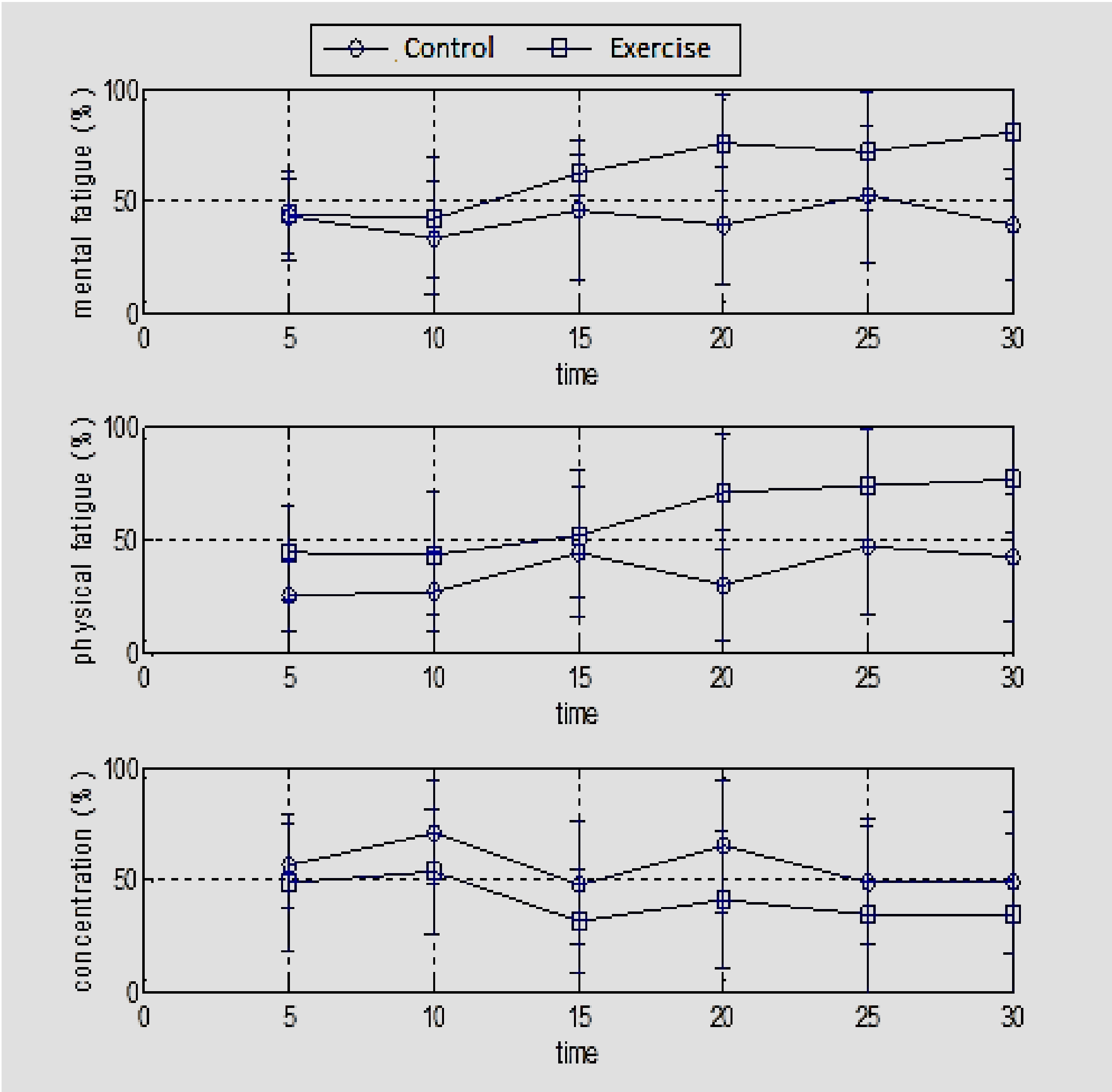

Figure 2. Energy-VAS subjective measures for the participants (n=12) under two conditions (control and exercise involved cognitive task).

3.1.2 Multi-Fatigue Inventory (MFI) subjective measures

A summary of results is shown in Table 1 depicting the mean value together with the respective standard deviation for each subjective measure, and for each experimental condition (control vs. exercise-involved) at the start and at the end of the cognitive tasks. There was a significant difference between the mean of each dependent variable subjected for both experimental conditions and also between pre and post each experimental condition ($p < 0.05$).

Table 1. Summary of the MFI measures obtained from the participants (n = 12) under these two conditions (control and exercise involved cognitive tasks). The double asterisk (**) denotes a statistical significance at $p < 0.01$ between the means of the subjective measures for pre-control and pre-exercise whereas the single asterisk (*) denotes a statistical significance between the means for post-control and post-exercise experimental condition with statistical significance $p < 0.05$.

Type of Fatigue / Type of Trial	General Fatigue	Physical fatigue	Reduced Activity	Reduced Motivation	Mental fatigue
Control (Pre)	5.5±1.8**	5.4±2.2**	5.3±1.9**	4.5±1.7**	4.3±1.2**
Control (Post)	10.6±2.6*	7.3±2.9**	9.0±2.9**	9.6±3.2*	13.3±1.7*
Exercise (Pre)	11.6±3.1**	11.8±2.6**	13.4±4.0**	9.6±2.7**	8.4±2.6**
Exercise (Post)	15.4±2.2*	15.5±2.3**	14.9±2.7**	14.0±4.2*	15.0±1.9*

3.2 Cognitive performance (Reaction Time and Accuracy)

The cognitive performance, in terms of reaction time of the participants in choosing the correct responses by pressing the appropriate key as well as the mean percentage of accuracy for all the participants subjected to these two experimental conditions, was evaluated for each 5 minutes time-on-task interval. The dependent variables that were reaction time and accuracy were analysed using two-way (2 experimental conditions x 6 time intervals) factorial ANOVA with repeated measures.

3.2.1 Reaction time performance

The mean reaction time of the participants in responding to the visual cues over the whole duration of the cognitive task for the control experiment was 475 ± 19.2 ms, and that for the exercise-involved experiment was 410.6 ± 16.6 ms.

It was observed that the reaction times decreased linearly with increasing time-on-task for the control experiment with reaction times at time5 (5 minutes elapsed) of cognitive task was 550 ± 20 ms and at time30 (30 minutes elapsed) was 405 ± 20 ms ($p < 0.01$), and the contrary was found for the exercise-involved task whereby reaction times increased linearly till to the completion of the cognitive experiment (time5 was 320 ± 10 ms vs. time30 was 470 ± 20 ms, $p < 0.01$). It was found that there was also a significant interactive effect between the repeated measures of time-on-task and experimental conditions ($F(6, 22) = 1418.8$, $p < 0.001$).

3.2.2 Accuracy performance

The participants performed significantly better ($F(1, 22) = 93.875$, $p < 0.01$) in the control trial with a mean percentage accuracy of (91.3 ± 1.2)% as compared to their accuracy of response performance for the exercise-involved cognitive trial which was (89.1 ± 1.4)%. However, there was no significant interactive effect between time-on-task and the two experimental conditions (p = 0.236, non-significant).

In both cognitive trials, it was found that the percentage accuracy of the responses decreased linearly based on the 6 data time intervals from time5 to time30. Furthermore, there was no significant difference ($p > 0.05$) in the percentage of accuracy of the responses of the participants for the control and exercise experimental conditions in counting mentally the low probability target visual cues that were the white squares and white circles randomly shown up on the screen for the Modified Stroop task.

3.3 EEG Analysis

In Figure 3, the notation Fzθ represents the theta band power at the frontal midline, the notation Pzα represents the alpha band power at the parietal midline of the brain and the cognitive ratio is the ratio of the frontal theta band power to the parietal alpha band power. For the whole duration of the cognitive trial, the mean (± standard deviation) of the theta band power, at the fronto-midline (Fz) for all the participants, was 6.76 (±1.74) μV^2 for the exercise-involved cognitive trial vs. 6.59 (±1.68) μV^2 for the control cognitive trial. Whilst the mean (± standard deviation) of the alpha band power of the participants at the parieto-midline (Pz) was 4.25 (±0.928) μV^2 for the exercise experiment as compared to 4.37 (±0.725) μV^2 for the control experiment. From the fronto-parietal network data analysis, it was found that there was no significant difference between the cognitive ratios computed for both exercise and control cognitive trials ($F(1, 22) = 3.140$; $p = 0.09$) even though the cognitive ratios were slightly higher for the exercise-involved cognitive trial than that of the control trial. However, there was a significant effect of the within subject factor time-on-task ($p < 0.01$), and there was also a significant difference in the cognitive ratio between the first 10 minutes (2.82 ± 0.31) of the cognitive trial as compared to that for the last 20 minutes (1.14 ± 0.16) of the cognitive trial for both experimental conditions (control vs. exercise-involved cognitive task trials, $p < 0.01$).

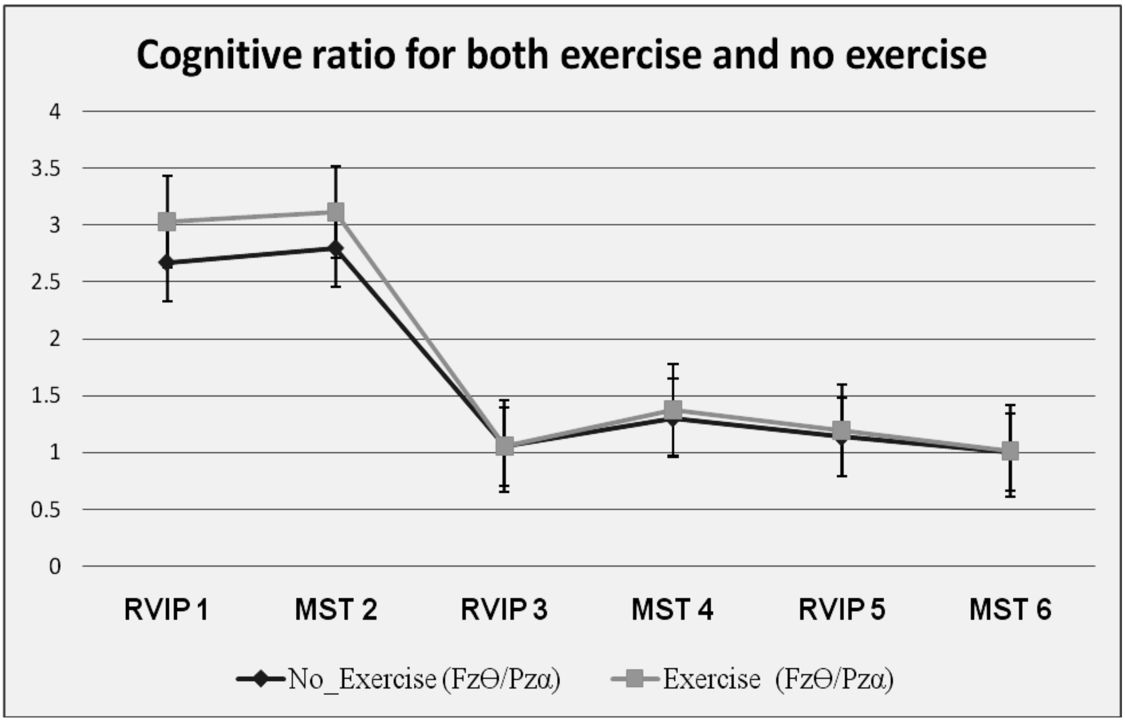

Figure 3. Cognitive ratio for both exercise-involved and no exercise (control) involved cognitive tasks ($n = 12$).

3.4 Entropy Analysis

A further investigation was conducted by analysing the entropy of the EEG signals in order to find out the amount of information flowing in the frontal and parietal regions in both conditions

(See Table 2). A 2-way factorial ANOVA with repeated measures (2 experimental conditions x 3 locations in the brain) was applied to the entropy data, and the statistical analysis revealed that there was a significant difference in the mean entropy between the frontal region (Fz) and the parietal (Pz) region ($p < 0.05$). In fact, the ratio of the entropy of the EEG signals at Fz to that of Pz for the control experiment was 0.867, and the ratio of the entropy of the EEG signals at Fz region to that of Pz for the exercise-involved cognitive task trial was 1.25.

Table 2 shows a summary of the entropy results of the EEG signals for the three brain regions (Cz, Fz and Pz) analysed in two experimental conditions (control vs. exercise) for 12 participants. The asterisk symbol * represents a statistical significance between the means of the entropy of EEG activities at Pz and Fz for both conditions with statistical $p < 0.05$.

Table 2. Descriptive statistics for entropy

Brain Locations	Conditions	Mean	Range	N
Cz	Control	2.0325	0.23542	12
	Exercise	2.0392	0.57619	12
	Total	2.0358	0.43046	24
Fz	Control	1.9958*	1.49913	12
	Exercise	2.3033*	0.92830	12
	Total	2.1496	1.22949	24
Pz	Control	2.3008*	1.31144	12
	Exercise	1.8408*	0.43025	12
	Total	2.0708	0.98300	24

4. Discussions

4.1 Questionnaire analysis (Fatigue-related subjective measures)

The visual analogue scales subjective measures showed that the participants felt more fatigued mentally and physically in the exercise-involved cognitive trial than the control experiment. Furthermore, there was an increase in the physical fatigue and mental fatigue as well as a decrease in concentration with increasing cognitive time-on-task trials for both experimental conditions. In the same line of thought, certain researchers [18, 38] showed that the subjective measures of fatigue were significantly greater than initial fatigue ratings as time-on-task increased. From the MFI results, both mental and physical fatigue subjective measures were significantly greater in the exercise-involved cognitive experiment than that of the control experiment. Furthermore, the participants felt more reduced motivation and reduced activity for the exercise-involved cognitive experiment than the control experiment as well as they felt more reduced motivation and reduced activity at the end than at the start of the experimental conditions. In addition, McMorris and Graydon (1996) stated that motivation would not increase with increasing time-on-task as the task demands were maintained same across trial blocks. In fact, for the exercise-involved cognitive trial, the author observed that most of the participants around time20 (20 minutes of the cognitive task had elapsed), started to feel very sleepy or tired (initiation of yawning processes) [24, 30] and they stated as post-study comments that they needed a 'good nap or sleep'.

4.2 Cognitive performance (Reaction time and Accuracy of responses)

Interestingly, the participants subjected to the exercise-involved cognitive experiment had overall a lower mean reaction time (or faster speed) in pressing the numerical keys when presented with a particular visual stimulus or when the chunk of odd or even numbers was found. However, the reaction time of the participants in the exercise-involved cognitive task increased exponentially with increasing time on task. In contrast to that, the reaction time of the participants for the control experiment decreases exponentially, and hence they performed at faster speed during the last time interval (time30) of the cognitive trial. Several researchers indicated a relationship between cognitive task length and response time. Firstly, one research study [29] found a non-monotonic effect on reaction time while another study [35] found a positive relationship between response time and cognitive task length. Furthermore, a mixed relationship was found [4] based on post error responses which was negative and post correct responses which was positive after either a medium or long-haul physical task performance. In this research study, the participants were more accurate in their responses during the control experiment than during the exercise-involved cognitive experiment. Couple with that, the accuracy of the responses to the visual cues decreased significantly for both experimental conditions as time-on-task increased. Lorist et al. (2000) emphasized a negative relationship between task duration and performance as response accuracy decreased significantly across the participants with increasing time-on-task. Another subjective report of fatigue [33] showed that as fatigue increased, response accuracy decreased independent of time-on-task. Certain researchers [53, 54] demonstrated that when the subjective reports of fatigue increased, the number of visual fixations increased as more fixations were needed to extract sufficient information from the visual scene which might contribute to a greater sensation of fatigue. Following a physical and a series of mental fatiguing task, the participants' arousal decreased based on the subjective measures of fatigue where they seemed to disengage from the task even though that the cognitive task demand was same across the cognitive block trials. Overall, the participants subjected to the control experiment performed better in terms of higher percentage accuracy of their responses but with slower reaction times than in the exercise-involved cognitive experiment. The following sections elaborate the results from the EEG analysis.

4.3 EEG analysis

There was no difference in the means of alpha band power at Pz and theta band power at Fz subjected to both experimental conditions. Moreover, there was no difference in the cognitive ratio (frontal theta band power to parietal alpha band power) between the two experimental conditions. However, there was a difference in the cognitive ratio with increasing time-on-task including an abrupt reduction in cognitive ratio after 10 minutes of the cognitive trial had elapsed for both control and exercise cognitive experiments. The decrements in cognitive function (cognitive ratio and poor accuracy) that were observed during the sustained mental work can be regarded as cognitive fatigue which subsequently prevented the alert participants to continue high mental performance [25, 40]. In addition, a progressive increase was found [36] in the EEG power in the frequency range of 4 Hz to 14 Hz as alertness decreased and error rates increased in a vigilance mental task. Cheng et al. (2007) found that there was a significant difference between the theta band and alpha band frequency power before a mental fatigued 3-hour visual display task session as compared to post session. When people feel fatigued during or after prolonged periods of cognitive activity, they have the tendency to lose concentration and cannot focus their attention on the tasks they are performing [3]. Furthermore, some researchers found that when arousal level dropped, EEG activities changed from fast and low amplitude waves to slow and high amplitude waves, and this decrease in arousal brought about a corresponding increase in low-frequency alpha and theta activities [27, 28, 43] which might be reflecting a decrease in cortical activation [11]. Hence, the amount of alpha and theta power can provide an indication of the level of fatigue which one experiences during mental fatiguing tasks [4].

4.4 Entropy analysis

As the cognitive ratio is based on a particular frequency range principle, the advantage of using the entropy mathematical method was that it considers the total information content of the EEG signal across the brain regions under investigation [52]. It was found that the mean entropy was significantly different between the fronto-midline and the parieto-midline regions of the brain, and the ratio of the entropies of these two brain areas was higher during the exercise-involved experiment than in the control experiment. Therefore, it appeared that there was an "overload" of information that prevented the participants in performing well, and remarkably, the cognitive ratio was also slightly higher during exercise than that of the control session. During competitive sporting environments, Mathews and Desmond (2002) stated that high task difficulty, prolonged task exposure and multiple task demands could induce a great level of information processing which subsequently increased the mental workload. Such increments in mental workloads caused a depletion of the cognitive system's resources that were available for task completion and consequently promoted the development of fatigue [37]. According to activation theory [23], the continuum ranging from low activation (e.g. sleep) to high activation (e.g. excited states) is a function of cortical bombardment by the ascending reticular activating system [49], and the relationship between activation and level of performance is represented by the inverted U curve [56]. This means that, with an increasing activation level, the level of performance increases monotically but after exceeding an optimal point, the relation becomes nonmonotonic which implies that further increase in activation level beyond this optimal point decreases the level of performance; this reduction in performance is related to the amount of increase in the level of activation. Therefore, the overflow of information as shown by the entropy ratio prevented the participants to focus properly their attention which might contribute to the reason why their response accuracy decreased specifically during the exercise-involved cognitive trial.

5. Conclusions

This research investigated whether there were finite metabolic resources in the brain by performing exhausting physical and cognitive tasks. The decreasing cognitive performance in terms of poor accuracy of responses, and faster reaction times following a tiring exercise-involved cognitive trial showed that there was definitely a change in the cognitive behaviour in the central system as compared to the control cognitive trial. According to the subjective measures of fatigue (i.e. reduced activity, motivation and concentration as well as increased mental fatigue and general fatigue), it was certain that the cognitive load which was perceived by the participants post a tiring physical activity seemed to increase even though the cognitive task demand placed mentally on them was kept constant throughout the cognitive trials. This insinuates that for a perceived 'cognitive load' to increase, there should be a decrease in the level of arousal or metabolic energy in the brain. In this research, the high cognitive ratio and information processing (i.e. entropy) across the fronto-parietal network during the exercise-involved cognitive trial impaired cognitive performance by decreasing the arousal state according to the inverted-U relationship of performance with increasing arousal level. It may be deduced from the research findings that the brain appeared to have finite metabolic resources. Therefore, for sport performance to be a peak level, the central systems should be equipped with necessary metabolic energy resources to reach optimum arousal and complete successfully a physical activity.

6. References

[1] Anderson, T. W. (1958). *Introduction to multivariate statistical analysis*. New York, John Wiley & Sons, Inc.

[2] Baumeister J, Reinecke K, Liesen H, Weiss M (2008). Cortical activity of skilled performance in a complex sports related motor task. *Eur. J Appl. Physiol*., 104, 625-631.

[3] Boksem, M. A. S., Meijman, T. F., & Lorist, M. M. (2006). Mental fatigue, motivation and action monitoring. *Journal of Biological Psychology*, 72, 123-132.

[4] Boksem, M. A. S., Lorist, M. M., & Meijman, T. F. (2005). Effects of mental fatigue on attention: an ERP study. *Cognitive Brain Research*, 25, 106-117.

[5] Bruhn J, Bouillon TW, Radulescu L, Hoeft A, Bertaccini E, Shafer SL (2003), 'Correlation of approximate entropy, bispectral index, and spectral edge frequency 95

(SEF95) with clinical signs of 'anesthetic depth' during co-administration of propofol and remifentanil', Anesthesiology, 3, pp. 621-7.
[6] Capuron, L., Welberg, L., Heim, C., Wagner, D., Solomon, L., Papanicolaou, D. A., Craddock, R. C., Miller, A. H., & Reeves, W. C. (2005). Cognitive dysfunction related to subjective report of mental fatigue in patients with chronic fatigue syndrome. *Neuropsychopharmocology*.
[7] Cheng, SY, Lee HY, Shu CM, Hsu HT (2007), 'Electroencephalographic Study of Mental Fatigue in Visual Display Terminal Tasks', J Med. Biol. Eng. vol 27(3). http://jmbe.bme.ncku.edu.tw/index.php/bme/article/view/215
[8] Chmura, J., Nazar, K., & Kaciuba-Uscilko, H. (1994). Choice reaction time during graded exercise in relation to blood lactate and plasma catecholamine threshold. *International Journal of Sports Medicine*, 15, 172-176.
[9] Chuckravanen, D. (2012). *Multiple system modelling and analysis of physiological and brain activity and performance at rest and during exercise.* Doctoral dissertation, Northumbria University, Newcastle, United Kingdom
[10] Corr, P. J. (2002). J.A Gray's reinforcement sensitivity theory: tests of the joint subsystems hypothesis of anxiety and impulsivity. *Personality and individual differences*, 33, 511-532.
[11]Cook, I, O'Hara R, Uitdehaage, SHJ, Mandelkern M, Leuchter AF (1998), 'Assessing the accuracy of topographic EEG mapping for determing local brain function', Electroencephalography and Clinical Neurophysiology, vol. 107, pp.408-414.
[12] Coull, J. T., Frith, C. D., Frackowiak, R. S., & Grasby, P. M. (1996). A fronto-parietal network for rapid visual information processing: a PET study of sustained attention and working memory. *Neuropsychologia*, 34(11), 1085-95.
[13] Cox, R. H. (1994). *Sport psychology: Concepts and applications*. Madison, WI: Brown & Benchmark.
[14] Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika*, 16(3), 297-334.
[15] Delignières, D., & Brisswalter, J. (1995). Effects of heat stress and physical exertion on simple and choice reaction time. *IXth European Congress on Sport Psychology*, Bruxelles.
[16] Dietrich, A. (2003). Functional neuroanatomy of altered states of consciousness: The transient hypofrontality hypothesis. *Consciousness and Cognition*, 12, 231-256.
[17] Dietrich, A., & Sparling P. B. (2004). Endurance exercise selectively impairs prefrontal dependent cognition. *Brain and Cognition*, 55, 516-524.
[18] Dureman, E. I., & Boden, C (1972). Fatigue in simulated car-driving. *Ergonomics*, 15, 299-305.
[19] Erfanian, A., & Mahmoudi, B. (2005). Real-time ocular artifact suppression using recurrent neural network for electro-encephalogram based brain-computer interface. *Medical and Biological Engineering and Computing*, 43, 296-305.
[20] Etnier, J. L., Salazar, W., Landers, D. M., Petruzzello, S. J., Han, M., & Nowell, P., (1997). The influence of physical fitness and exercise upon cognitive functioning: a meta-analysis. *Journal of Sport Exercise Psychology*, 19 (3), 249–277.
[21] Fasano, G., & Franceschini, A. (1987). A multidimensional version of the Kolmogorov–Smirnov test. *Monthly Notices of the Royal Astronomical Society*, 225, 155–170, ISSN 0035-8711.
[22] Gevins A., Smith ME, McEvoy L, Yu D. (1997). High resolution mapping of cortical activation related to working memory: effects of task difficulty, type of processing, and practice. *Cereb. Cortex*, 7, 374-385.
[23] Hebb, DO. (1955), 'Drives and the C.N.S (Conceptual Nervous System)', Psychological Review, 62, pp. 243-254. http://psychclassics.yorku.ca/Hebb/.

[24] Hermanowicz N. (2007), 'Cranial nerves IX (glossopharyngeal) and X (vagus). In: Goetz CG, ed. Textbook of Clinical Neurology. 3rd ed. Philadelphia, Pa: Saunders Elsevier, Chapter 13.
[25] Hockey, GRJ (1997) 'Compensatory control in the regulation of human performance under stress and high workload: A cognitive energetical framework. Biological Psychology, 45, pp. 73-93.
[26] Holm, A., Lukander, K., Korpela, J., Sallinen, M., & Muller K. M. I. (2009). Estimating brain load from the EEG. *The Scientific World Journal*, 9, 639-651.
[27] Klimesch, W. (1997), 'EEG alpha rhythms and memory processes' International Journal of Psychophysiology, vol., 26, pp. 319-340.
[28] Lafrance C, Dumont M (2000), 'Diurnal variations in the waking EEG: comparison with sleep latencies and subjective alertness', Journal of Sleep Research, vol. 9, pp. 243-248.
[29] Levitt, S., & Gutin B (1971). Multiple choice reaction time and movement time during physical exertion. *Research Quarterly*, 42, 405-410.
[30] LeWinter MM. (2007), 'Pencardial diseases. In: Libby P, Bonow RO, Mann DL, Zipes DP, eds. Braunwald's Heart Disease: A Textbook of Cardiovascular Medicine', 8th ed. Philadelphia, Pa: Saunders Elsevier, chap 70.
[31] Lopes, R. H. C., Reid, I., Hobson, P.R. (2007, April 23–27). The two-dimensional Kolmogorov-Smirnov test. *XI International Workshop on Advanced Computing and Analysis Techniques in Physics Research*, Amsterdam, the Netherlands.
[32] Lord, S. W., Clayton, R. H., Hall, M. C. S, Gray, J. C., Murray, A., McCOMB & Kenny R. A. (1998). Reproducibility of three different methods of measuring baroflex sensitivity in normal subjects. *Clinical Science*, 95, 575-581.
[33] Lorist, M. M., Klein, M, Nieuwenhuis, S., De Jong, R., Mulder, G., & Meijman, T. F. (2000). Mental fatigue and task control: Planning and preparation. *Psychophysiology*, 37, 614-625.
[34] Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, 31, 291-308.
[35] Macchi, M. M., Boulos, Z., Ranney, T., Simmons, L., & Campbell, S. S. (2002). Effects of an afternoon nap on nighttime alertness and performance in long-haul drivers. *Accident Analysis and Prevention*, 34, 825-834.
[36]Makeig, S and Inlow, M (1993), 'Lapses in alertness: coherence of fluctuations in performance and the EEG spectrum', Electroencephalogr. Clin. Neurophysiol., 86, pp. 23-25.
[37] Matthews, G., and Desmond, P.A (2002). 'Task-induced fatigue states and simulated driving performance', The Quaterly Journal of Experimental Psychology, 55A(2), pp. 659-686.
[38] Matthew, R., (2004). Physiological methods and measurements in driving simulation. *Proc. of the human factors and Ergonomics Soc. Annual Meeting*, 48(19), 2330-2334.
[39] McMorris, T. & Graydon, J. (1996). The effect of exercise on soccer decision-making tasks of differing complexities. *Journal of Human Movement Studies*, 30, 177-193.
[40] Montgomery, LD, Montgomery RW et al. (1995) 'Rheoencephalographic and electroencephalographic measures of cognitive workload: analytical procedures. Biol. Psychol., 40, pp. 143-159.
[41] Nash, A. J., Williams, C. S. (1982). Effects of preparatory set and task demands on auditory event-related potentials. *Journal of Biological Psychology*, 15(1-2), 15-31.
[42] Nideffer, R. M. (1993). Concentration and attention control training. In JM Williams (Ed.), *Applied sport psychology: Personal growth to peak performance*, 243-261, Toronto, Mayfield.

[43]Oken BS, Salinsky M (1992), 'Alertness and attention: basic science and electrophysiologic correlates', Journal of Clinical Neurophysiology, vol. 9(4), pp. 480-494.
[44] Paas, F. G. W. C. & Adam, J. J. (1991). Human information processing during physical exercise. *Ergonomics*, 34, 1385-1397.
[45] Schmitt, N. (1996). Uses and abuses of coefficient alpha. *Psychological Assessment*, 8, 350-353.
[46] Seber, G. A. F. (1984). *Multivariate observations*. New York: John Wiley & Sons, Inc.
Shannon C. E. (1949, January). Communication in the presence of noise. *Proc. Institute of Radio Engineers*, 37 (1), 10–21. Reprint as classic paper in: Proc. IEEE, vol. 86, no. 2, (Feb. 1998)
[47] Shannon, C.E. (1948). A mathematical theory of communication. *Bell System Technical Journal,* 27, 379–423.
[48] St Clair Gibson, A., Noakes T. D. (2004). Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *British Journal of Sports Medicine*, 38, 797-806.
[49] Steriade, M. (1996). 'Arousal: Revisiting the reticular activating system', Science 272 (5259), pp. 225–226.
[50] Tomporowski, P. D. (2002). Effects of acute bouts of exercise on cognition. *Acta Psychologica Scandinavia*, 112(3), 297-324.
[51] Uetake, A., & Murata, A. (2000). Assessment of Mental Fatigue during VDT task using event-related potential (P300). *Proc. of the 2000 IEEE International Workshop on Robot and Human Interactive Communication*, Osaka, Japan.
[52]Viertio-Oja H, Maja V, Sarkela M., Talja P., Tenkanen N, Tolvanen-Laakso H, Paloheimo M, Vakkuri A, Yli-Hankala A, Merilainen P (2004), 'Description of the Entropy algorithm as applied in the Datex-Ohmeda S/5(TM) Entropy Module', *Acta Anaesthesiol*. Scand, 48, pp. 154-161.
[53]Williams AM, Davids K and Williams K (1999). *Visual perception and action in sport*. London: E and FN Spon.
[54]Williams AM (2000), 'Perceptual skill in soccer: Implications for talent identification and development', *Journal of Sport Sciences*, 18, pp. 737-750.
[55] Wright, T. P. (1936). Factors Affecting the Cost of Airplanes. *Journal of Aeronautical Sciences*, 3(4), 122-128.
[56] Yerkes, R.M. & Dodson, J.D. (1908). 'The Relation of Strength of Stimulus to Rapidity of Habit-Formation', Journal of Comparative Neurology and Psychology, 18, pp. 459-482.