AN EXPERIMENTAL STUDY OF DRIVER FATIGUE

BY

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AN EXPERIMENTAL STUDY OF DRIVER FATIGUE:
SUBJECTIVE DRIVER FATIGUE SCORE, DRIVING PERFORMANCE, AND DRIVER FATIGUE COUNTERMEASURES

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LAY ABSTRACT

In this project, two experiments were conducted to study driver fatigue. A subjective driver fatigue score was specially developed and used as a driver fatigue indicator. This score was sensitive to driver fatigue changes, and showed a linear relationship with the standard deviation of lateral acceleration. Two popular driver fatigue countermeasures, caffeine and music, were examined to investigate the effects on subjective driver fatigue and driving performance. The results showed that caffeine reduced subjective driver fatigue and helped driver maintain good driving performance; however, music only helped drivers reduce subjective driver fatigue.

Abstract

Two experiments were conducted to study driver fatigue. The first investigated driver fatigue and driving performance. Thirty one Participants completed a questionnaire to obtain their Subjective Driver Fatigue Score (SDFS) quantifying fatigue levels. Driving performance was evaluated by measuring steering wheel, lateral position, etc. The results showed significant increases in the SDFS and driving performance impairment following simulated driving sessions. Further analysis suggested a linear relationship between the SDFS and the standard deviation of lateral acceleration. Subjective fatigue assessment and driving performance were plotted as radar diagrams to show the multidimensional characteristics. The second experiment examined effects of caffeine and music on the SDFS, driving performance, and 8 EEG signal parameters. Initially, there was no significant inter-sessional variation in the dependent variables, suggesting all sessions were started at similar states. The final SDFS for caffeine and music sessions were significantly lower than control sessions, suggesting both inhibited subjective fatigue increase. Driving performance deteriorated less significantly in caffeine sessions than in control and music sessions. The results suggested that caffeine was more effective than music. EEG was not changed significantly. However, the amplitude of α wave increased significantly for an extremely fatigued individual, along with vehicle drifting and micro-sleep. In conclusion, the SDFS developed in this study successfully estimated subjective driver fatigue levels and showed a linear relationship with driving performance during driving tasks. Caffeine and music reduced driver fatigue subjectively similarly, but caffeine also helped subjects maintain driving performance.

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Nomenclature

A	Power spectrum of EEG signal
AC	longitudinal acceleration (feet/s^2 or meter/ s^2)
DFQ	Driver fatigue questionnaire
LA	Lateral acceleration (feet/ s^2or meter/ s^2)
LKT	Lane keeping task
LP	Lateral position (feet, or meter)
LV	Lateral velocity (feet/s or meter/s)
Q	The score of individual item in the questionnaire
R	The EEG indicator
SA	Angular position of steering wheel (degree)
SD	Standard deviation
SDFS	Subjective driver fatigue score
SR	steering wheel rate (rad/s)
VE	longitudinal velocity (feet/s or meter/s)
YR	Yaw rate (rad/s)

Subscripts

m	the index of the subject
n	the index of record
	the index of items in the questionnaire
t	Driving time
α	α band
β	β band
θ	θ band
δ	δ *band*
Δ	Mean of standard deviation

Declaration of Academic Achievement

The following is a declaration that the content of the research in this document has been completed by ShiXu Liu and recognizes the contributions of Dr. Shengji Yao, Dr. Allan Spence, and Dr. Hubert de Bruin in both the research process and the completion of the thesis. ShiXu Liu contributed to the study design and was responsible for data collection, data analysis and writing of the manuscript. Dr. Shengji Yao and Dr. Allan Spence assisted with the experiment design, data analysis, and manuscript review. Dr. Hubert de Bruin assisted with EEG data collection and analysis.

Chapter 1 Introduction

Nowadays, the global village is becoming the world on wheels. For more and more people, driving is a part of their daily life. After the automobile was invented, it had a generally beneficial impact. For example, automobiles allow people to travel longer distances and to ship heavier cargo rapidly. However, heavy vehicles traveling at high speed are very destructive should an accident occur. Therefore, driving safety has long been an important social concern for drivers and road sharers. During the last several decades, new technologies and advanced designs have made today's automobiles different from those in the old days; however, safety has remained an important societal concern. The current research is intended to help drivers to improve road safety. More specifically, this research experimentally (1) studies driver fatigue and its influence on driving performance, and (2) investigates two fatigue countermeasures which are frequently employed by drivers.

In this chapter, the background of the research is discussed in the next section, explaining why the interests in driver fatigue have been brought into the current study.

The second section states the objective of the study, followed by the challenges of the study in the third section. The contribution of this study is summarized in the fourth section. The last section of this chapter provides the outline of the thesis.

1.1 Background

Around the world, thousands of people die or are injured because of traffic accidents every year. For example, according to the reports from Transport Canada from 2010 to 2012 , 3233 drivers, 1304 passengers, and 923 pedestrians lost their lives because of traffic accidents in Canada [1-3]. Accidents may also lead to loss of property, serious injuries, and psychological barriers in driving for someone. Therefore, drivers should do their best to avoid a traffic accident. Traffic accidents can be caused by operational errors such as running red lights, running stop signs, unsafe lane changes, wrong-way driving, improper turns, tailgating, etc., or unsafe driving behaviors including reckless driving, road rage, speeding, street racing, etc., or environmental difficulties such as heavy rain, fog, snow, etc., or bad road conditions such as icy road surface, deadly curves, unexpected potholes and/or animal crossings, etc., or influence of alcohol and/or drugs, or vehicle component defects such as tire blowouts. Other factors can also cause traffic accidents, examples include conversation during driving, night driving, and drowsy driving. Drivers can easily avoid accidents resulting from some of the causes listed above. For instance, alcohol consumption can be detected by estimating blood alcohol content to prevent drunk driving; cell phone use can be stopped to prevent distraction from driving; warning signs can be installed well ahead to provide notice of entering animal crossing zones. However, driver fatigue accumulates during driving tasks and is difficult to detect, especially at its early stage. If a driver is fatigued enough and falls asleep behind the wheel, it is usually too late! Therefore, driver fatigue has attracted attention from many researchers [4-6] and government organizations [7]. Evidence shows that driver fatigue is one of the major causes of traffic accidents [8]. Research conducted in Australia revealed that 25~35% of fatal traffic accidents were related to driver fatigue [9]. Another study reported that 58% of all traffic accidents in the U.S. were caused by driver fatigue [10]. Better understanding the mechanism of driver fatigue can help drivers to (1) effectively manage fatigue induced during driving, (2) apply appropriate fatigue countermeasures to reduce fatigue level, and (3) make wise decisions to avoid driving with fatigue, and therefore, reduce fatigue related traffic accidents. The current study aims to experimentally examine (1) how driving performance is affected by driver fatigue and (2) how fatigue countermeasures affect fatigue levels and driving performance in prolonged driving tasks. The results of this study may be helpful in future development of a driver fatigue monitoring/warning system that assists the driver in maintaining road safety.

1.2 Objective

The objective of this study was to better understand the mechanism of driver fatigue, its influence on driving performance, and effectiveness of fatigue countermeasures. Two experiments have been conducted in this study. The first experiment investigated the relationship between subjective driver fatigue levels and driving performance in simulated driving tasks. The second experiment investigated the effectiveness of caffeine and music as fatigue countermeasures in simulated driving tasks.

To understand the mechanism of driver fatigue, it was necessary to choose an appropriate driver fatigue measuring method, or driver fatigue indicator, to identify various driver fatigue levels. Therefore, the first objective for the current study was to develop a Subjective Driver Fatigue Scale (SDFS) to quantify fatigue levels of the driver.

In the first experiment, the SDFS was examined during simulated driving sessions to check its validation and sensitivity to driver status. The second objective was to investigate changes in the SDFS and driving performance throughout the prolonged simulated driving tasks. Then how variations in driver fatigue, which was estimated by the SDFS, affect driving performance was examined.

Another objective was to examine effectiveness of caffeine and music as driver fatigue countermeasures in simulated driving tasks. Driver fatigue levels were examined under different driving conditions, in which the driver adapted to various fatigue countermeasures. Driving performance was also examined to analyze the effectiveness of caffeine and music. Brain activities, reflected by the electroencephalograph (EEG), have been recognized as a reliable estimation of fatigue [8]. Therefore, EEG signals were examined to check whether EEG analysis was able to be employed as an online driver fatigue indicator to monitor driver status and detect driver fatigue in early stages.

1.3 Challenges

Although drivers commonly experience fatigue after prolonged driving tasks and researchers have studied fatigue for decades, there are difficulties in agreement on a generally accepted definition of fatigue [8, 11]. This is a challenge faced by researchers studying fatigue and its related subjects, as well for the current study in driver fatigue. A literature review has been conducted to look for an acceptable definition of driver fatigue for the content for the current study. Although, this definition of driver fatigue may not be accepted by all researchers studying driver fatigue, it should properly describe and distinguish the characteristics of driver fatigue.

The second challenge of this study is how to accurately quantify driver fatigue, especially during driving tasks. Previous studies have developed various fatigue indicators, which can be categorized into physiological measurements (such as EEG), psychomotor measurements (such as simple reaction time tests), and subjective assessments (such as the Stanford Sleepiness Scale) [8, 12, 13]. However, it remains undetermined which of these fatigue indicators can quantitatively estimate driver fatigue accumulating during driving tasks. For example, traditional EEG devices are usually inconvenient to implement and therefore are often used only in off-road studies. Psychomotor measurements usually require participants focusing only on the psychomotor task to obtain accurate estimation. Therefore, it is necessary to determine whether psychomotor tests, such as a simple reaction time test, can reflect real driver status while driving. On the other hand, existing subjective assessment tools are designed for general or clinical purposes instead of estimation of driver fatigue. Therefore, to better understand the mechanism of driver fatigue, finding a suitable indicator is a challenge for this study.

The third challenge of this study is how to examine effectiveness of caffeine and music as driver fatigue countermeasures, and how to distinguish the differences between the two countermeasures. Drivers in a long journey often employ various countermeasures to fight fatigue. While subjectively feeling that countermeasures are useful, drivers seldom report to what degree the countermeasures help them keep awake or alert. It is necessary to examine the differences between the condition utilizing a countermeasure and the condition without utilizing the countermeasure. The parameters chosen for examining the effectiveness should have abilities to reflect variations in driver status. The parameters need to be able to identify the different degrees of the effect under conditions utilizing different countermeasures. These parameters may include subjective assessment and objective assessment of driver status. The Stanford Sleepiness Scale is an example of a subjective assessment, and EEG analysis is an example of an objective assessment.

The fourth challenge of this study is to control traffic conditions so that every subject can have the same experiences during driving tasks. This is essential because it is desirable to minimize the variation in driver status resulting from variations in traffic conditions. If subjects do not experience the same traffic condition, variation in driver fatigue may include two components: driver fatigue variation resulting from driving tasks (task component) and resulting from variation in traffic conditions (traffic component). However, to separate the task component from the traffic component is not easy. With precisely controlled traffic conditions, which can be achieved by using a computerized driving simulator, the variation in driver fatigue is the result of the driving task.

1.4 Contributions

The current study aims to better understand driver fatigue by investigating (1) subjective driver fatigue levels, (2) driving performance, and (3) effectiveness of caffeine and music as driver fatigue countermeasures. To estimate subjective driver fatigue levels, a questionnaire has been developed, so that the Subjective Driver Fatigue Score can be obtained by summing scores of each item in the questionnaire. Two experiments were then conducted. The first experiment examined how driver fatigue increased and how driving performance deteriorated with driving time. Each subject completed three 45-minute driving sessions, with 3 to 5 minute breaks between driving sessions. The Subjective Driver Fatigue Score was used to quantify driver fatigue and 16 parameters were used to determine driving performance. A linear relationship between the Subjective Driver Fatigue Score and driving performance was found. Multidimensional representation of the Subjective Driver Fatigue Score and driving performance help drivers better understand their status during driving tasks.

The second experiment examined effectiveness of two fatigue countermeasures, caffeine and listening to music. Each subject completed three 120-minute control, caffeine, and music sessions. The SDFS and driving performance were used to investigate the effectiveness. The SDFS after the control session was higher than caffeine and music sessions, indicating caffeine and music helped the subject maintain low fatigue levels. Driving performance after the caffeine session deteriorated less than after the control and music sessions, indicating caffeine helped the subject to maintain good driving performance. After 120 minutes, caffeine helped the subject maintain low fatigue levels and good driving performance. Similarly, music helped the subject maintain low fatigue levels; however, music did not help the subject to maintain good driving performance. The second experiment also provided the protocol to study other driver fatigue countermeasures.

The successful development and application of the driver fatigue indicator have been validated in the experiments. The evidence showed that this fatigue indicator was more sensitive than the general subjective fatigue assessment tools, such as the Stanford Sleepiness Scale. To date, there has been no fatigue indicator that was specially developed for drivers. To the best of my knowledge, this was the first subjective assessment tool for evaluating fatigue of an individual performing a driving task. An important contribution of the first experiment was the linear relationship suggesting increases in standard deviation of lateral acceleration with increasing subjective driver fatigue scores. This finding was helpful in developing fatigue and performance detecting/predicting systems. On the other hand, the radar diagram demonstrated the five sub scores of the questionnaire and revealed the characteristics of fatigue that experienced by the driver. This finding contributed to the appropriate choice of the fatigue countermeasure needed for different types of fatigue; therefore, the driver would maintain sufficient alertness level to drive safely. The second experiment provided quantitative comparison between the two fatigue countermeasures, caffeine and music. It was evident that both kept the subjective driver fatigue score at relatively low levels. However, while caffeine also helped the subjects to inhibit deterioration of driving performance, music introduced additional distraction and did not improve driving performance. The findings of the second experiment provided a guideline to the driver to choose a suitable fatigue countermeasure under different fatigue situations. It also provided a protocol to examine effectiveness of other fatigue countermeasures that were not examined in the current study.

1.5 Thesis organization

The thesis consists of seven chapters. The first chapter is the introduction. The second chapter is the literature review. The third chapter describes the development of the SDFS and its calculation. The fourth chapter gives details of the experimental design. The fifth and sixth chapters provide the data analysis of the experiments. The last seventh chapter discusses the findings of the project and concludes the study and possible future work.

Chapter 2 Literature Review

In this chapter, some fatigue related research is reviewed. The purpose of this review is to better understand the previous research on driver fatigue. General fatigue and driver fatigue are to be considered first in section 2.1. Secondly, various fatigue indicators developed by previous researchers are discussed in section 2.2. Then, driving performance variables are discussed and summarized in a list in section 2.3. Finally, various driver fatigue countermeasures are taken into consideration in section 2.4.

2.1 Fatigue and driver fatigue

Fatigue is a common phenomenon and has an impact on performance of individuals. When performing risky tasks, fatigue can cause dangerous errors. Therefore, many researchers of different areas have made efforts to understand the mechanisms of fatigue [14-25]. Some researchers focused on fatigue in industrial [12] and military [20] areas for healthy people. Some other experiments were conducted to investigate fatigue and its effects on people with illness [17, 26, 27]. Experiments were also conducted to examine the effects of fatigue on performance in athletes [21]. Many experiments have also been conducted to study fatigue related to driving tasks [18, 22, 24, 28-31]. However, there is no absolute agreement on the definition of fatigue [8]. Although, this review on fatigue related research is not intended to draw a generally accepted definition, it is necessary to properly address the content of the current study of driver fatigue by a definition, which will be provided at the end of this section.

2.1.1 Fatigue in general

Fatigue symptoms are the most useful indicators in identifying fatigue. Fatigued people exhibit symptoms including: lapses of attention; operational errors and distractibility; reduced rate of information processing; more variable task performance; and reduced reserve capacity [32]. Fatigue is often classified into physical fatigue and mental fatigue. Physical fatigue is related to muscular fatigue, and mental fatigue is related to psychological phenomena such as impaired awareness and diminished motivation [8].

Muscular fatigue is usually reflected by reduced muscular power and slowed body movement [12]. Lactic acid and carbon dioxide accumulate while muscular fatigue occurs, and people usually find the muscular tissue becomes acidic, due to consumption of energy reserves (such as glucose and phosphorous) to supply energy needed for human activities. Sufficient physical rest and energy intake are necessary for muscular fatigue recovery, during which the muscular tissue regains a normal internal environment. People can usually notice muscular/physical fatigue by themselves, through physical fatigue symptoms such as slowed movement, reduced muscular capacity, muscle soreness, etc. Impairment in performance caused by physical fatigue, therefore, can be clearly identified. However, it is worth noting that the mechanism of some fatigue symptoms is not fully understood. For example, two groups of researchers, Lewis et al. and Cheung et al., mentioned six hypothesized theories explaining the mechanism of delayed muscle. Both of them suggested that a single theory was not sufficient to explain the causes of muscle soreness [33, 34]. It is interesting that, according to the report from Cheung et al., lactic acid, which has been believed to be the cause of muscle soreness, may be related to muscle soreness immediately after intense exercise, but is not the cause of the delayed onset of muscle soreness [34].

Mental fatigue, on the other hand, is a complex psychological phenomenon. It is often exhibited by symptoms including (but not limited in) a disinclination for effort, and reduced efficiency and degraded alertness [12]. Mental fatigue increases gradually and can accumulate while performing a task continuously. Although mental fatigue can also be self-identified when it becomes severe, people usually have difficulty to self-recognize the onset of mental fatigue. In general, by the time an individual self-recognizes fatigue, this individual is already in a very serious fatigue condition. If he/she is performing a task involving any risks, such as driving a car, impaired performance may put him/her and others in a dangerous situation. In addition, physical fatigue and mental fatigue can affect each other, and an individual can also experience a combination of the two [8]. For example, after driving for a long time period, the driver may get sleepy and experience sore feet; this driver then experiences physical fatigue and mental fatigue simultaneously.

2.1.2 Driver fatigue

Driving is a risky task involving both physical fatigue and mental fatigue if proceeding long enough. Therefore, symptoms developed during a continuous driving task include physical symptoms (such as sore feet, tired eyes, feeling drowsy, etc.) [18] and psychological symptoms (such as slow-downed reaction, being distractible, etc.) [8]. Severe fatigue does cause impairment in driving performance, which may directly lead to road accidents. Therefore, it is important to monitor driver fatigue and help drivers avoid accidents caused by driver fatigue.

Numerous studies have been conducted to develop measurable parameters associated with driver fatigue. Fatigue indicators that have been developed may be categorized into physiological measurements (such as the electroencephalogram), psychomotor measurements (such as simple reaction time), body motions (such as head or eyelid movement), and subjective assessment based on self-reported fatigue symptoms [8, 12, 13]. Driving performance is impaired with increased driver fatigue; therefore, parameters used to estimate driving performance can also be used as fatigue indicators. Some frequently measured driving performance parameters include the mean and the standard deviations of vehicle velocity, lane position, steering wheel rate, lateral acceleration, etc. [35-38]. A thorough list of driving performance parameters is provided in section 2.3.

To reduce/avoid road accidents associated with driver fatigue, various fatigue countermeasures are often employed by drivers. For example, some drivers believe that opening the window while driving can help to reduce fatigue induced by prolonged driving. Automobile designers are interested in whether these fatigue countermeasures are effective and how long the effect can last [4, 39-41]. Detailed discussion on driver fatigue countermeasures is provided in section 2.4.

Based on the characteristics of driver fatigue and its effects on driving performance, the modified definition given by Williamson will be adapted in this study: "[fatigue is] a state of reduced mental alertness [and muscular functions], which impairs performance of a range of cognitive and psychomotor tasks, including driving [35] "

2.2 Fatigue indicators

Efforts have been made by researchers to develop variables associated with fatigue. Various commonly used fatigue indicators include performance, perceptual, electrophysiology, psychological and biochemical measurements, etc. Fatigue indicators associated with industry are categorized into several groups [12]. These include quality and quantity of work performance, recording of subjective impressions of fatigue, electroencephalography, measuring subjective frequency of flicker-fusion of eyes (also called eye/eyelid movement), psychomotor tests and other mental tests, etc. Fatigue indicators associated with driving were recently categorized into groups differently [13]. These include subjective assessment, psychomotor test, ocular parameters, physiological variables, and other methods such as steering grip pressure, skin conductance, blood volume pulse, etc. Some frequently used fatigue indicators of these are reviewed in this section.

2.2.1 Subjective fatigue assessment

Subjective fatigue assessment is a traditional key measure in fatigue related studies [11, 27, 35, 42, 43]. While some researchers considered subjective assessment of driver fatigue based on questionnaires as important fatigue indicators [12, 18, 19, 38, 42-45], other researchers pointed out that the questionnaire was usually completed before or after the driving experiment and on-task estimation was not available, and that subjective assessment alone was inadequate [8]. However, because subjective fatigue assessment is simple, direct, nonintrusive, and reasonably reliable, it has recently received more and more attention [10, 13, 18, 28, 36, 38, 44, 46, 47]. For example, some experiments have been conducted to investigate how the changes in subjective fatigue score are related to changes in performance (such as steering wheel movement, lane position deviation, etc.) [36, 39, 48, 49].

Fatigue symptoms are important in identifying driver status. An experiment was conducted to investigate how fatigue symptoms (such as headache, backache, sore feet, eye strain, etc.) developed during simulated driving tasks [18]. In the experiment, subjects were asked to drive as long as possible, until they could not continue. A questionnaire was used to estimate the severity of physical fatigue symptoms. Driving time that a driver could persist in was found different for individuals. Regardless of how long the driving time persisted, drivers stopped driving when a “critical fatigue level” was reached. A modified Pearson Fatigue Checklist was used, and a physical symptom questionnaire for self-reported fatigue assessment was developed. The study concluded that (1) people stopped driving at similar fatigue levels, (2) but how quickly each individual reached the critical level of fatigue differed. It was also found that some physical symptoms did not increase, while others increased linearly with time during a simulated driving task. Backache, headache, stiff joints, and numbness showed significant increase while sore feet, tired eyes, and drowsiness developed most quickly with driving time elapsed. This study suggested that the Pearson Fatigue Checklist provided a valid measure of fatigue in the simulated driving task [42]. From this study, the symptoms that are useful as fatigue indicators are tired eyes, sore feet, drowsiness, backache, headache, stiff joints, and numbness, because these symptoms quickly developed during the driving tasks. While the current experiment investigated changes in fatigue symptoms with driving time, the experiment described in the next paragraph investigated effects of driving condition on driver fatigue [36].

Traffic situations, as a source of stimulation, have impacts on driver status. To investigate environmental effects, an experiment was conducted [36]. Subjects were asked to complete simulated driving tasks in monotonous/less monotonous traffic conditions. The study examined effects on fatigue in two types of traffic situations, rather than time effects. Subjective fatigue was measured using a seven point Likert-type scale. Driving performance was determined through steering wheel movement and lateral position. Increase in steering wheel movement and lateral positon (and its standard deviation) were used as signs of the deterioration of driving performance. The results showed that variance in driving performance deteriorated more in monotonous road conditions than in less monotonous road conditions. The seven point Likert-type subjective fatigue scale was simple and direct. It was rapidly and briefly answered by the subjects, to avoid (or reduce) possible changes in current fatigue levels of the drivers. While some experiments examined fatigue changes through simulated driving tasks [18, 36], the following experiment examined changes in fatigue levels through real road driving tasks.

In a real road driving study [50], the results showed that verbal subjective assessment of driver state has impacts on the drivers. While the experiment was conducted on a real road, effects of verbal assessment of subjective fatigue were investigated, using objective indicators of vigilance states including EEG, eye-blink duration, and heart rate. The results showed that fatigue level was significantly reduced during verbal subjective fatigue assessment. Reaction times also decreased after verbal subjective assessment, indicating fatigue level was reduced. This fatigue reduction effect dissipated two minutes after the end of the verbal communication. The study confirmed reduction in driving fatigue induced by verbal communication. Therefore, when subjective fatigue is estimated verbally, this effect should be taken into consideration, although the effect only lasts about two minutes.

2.2.2 Psychomotor and mental tests

The second type of fatigue indicator employs psychomotor and/or mental tests such as a reaction time test and/or arithmetic test to estimate the cognitive aspect of driver fatigue [48, 51-57]. Deteriorated performance on psychomotor tests is assumed to be related to increased fatigue levels. For example, slower typing speed or increased typing error rate is a sign of fatigue increase.

Simple reaction time tests have been employed in a recent study in developing a mathematical model to describe the relationship between human sustained attention performance (reaction time) and fatigue induced by sleep deprivation [56]. This model has been used in an experiment to investigate the performance of the driver with sleep deprivation [57]. In the experiment, drivers were asked to complete a forty-minute driving session once a day for four consecutive days. The driver did not experience sleep deprivation on the first day. On the second day, the driver was restricted to four hours of sleep. Then the driver had no sleep for one day on the third day and no sleep for two days on the fourth day. The drivers completed the driving tasks between 2:00 pm and 4:00 pm. Driving performance such as deviation of lane position was recorded. The results showed that deviation of lane positon increased with sleep loss. The model developed based on sustained attention performance well predicted degradation in driving performance, but underestimated true driving performance.

The arithmetic test is an example of a psychomotor test, which involves basic numerical calculation. Arithmetic tasks were performed by subjects in an experiment, which was conducted to investigate the effects of traffic conditions on driver fatigue [48]. The arithmetic task included additions and subtractions, and the subjects provided the answer orally. During the experiment, the subjects experienced traffic conditions with different levels of complexity. Driver fatigue was measured by a questionnaire, a visual traffic sign distance estimation task, and the arithmetic task. Driving performance was measured in terms of mean and standard deviation of steering wheel movement, etc. The results showed that after one hour of driving, subjective driver fatigue increased, accompanied with greater attention demand. Increase in driver fatigue was more significant in the complex traffic condition than in the monotonous condition. The subjects tended to overestimate the distance between the vehicle and the road-side traffic signs. However, performance of visual distance estimation was better under the complex traffic condition than the monotonous condition. Performance on the arithmetic task was also better under the complex traffic condition. The researcher also pointed out that the performance on the arithmetic task was better for fatigued subjects. This study indicated that driver fatigue increased when traffic conditions became monotonous, and decreased when traffic conditions became complex; because more complex traffic conditions require more attention [48].

2.2.3 Eye movement

When people are fatigued, their eyes move in certain patterns, and this can be used as a fatigue indicator. The pattern of eye movements has been studied to develop fatigue indicators by some researchers [30, 58, 59]. Eye movements are usually fast at normal conditions for people with no fatigue, but become slow and small when people become fatigued. Sometimes fast rhythmic blinks can be observed with fatigue [8]. Electrooculography (EOG) is used to monitor eye movements; therefore, changes in EOG can be used to identify fatigue. The percentage of eye closure (PERCLOS) is an alternative fatigue indicator. This method was employed by some researchers [51] as an independent fatigue indicator to verify the subjective fatigue estimates. Other researchers [59-61] developed eye tracking systems to detect driver fatigue. For example, a prototype including an eye tracking system has been developed to dynamically monitor the whole face of the driver, enabling real-time detection of driver fatigue [60].

Combining facial expression and characterized movements of eyelid, gaze, and head, the system was found to be more reliable than other fatigue monitoring systems in which only a single fatigue indicator was employed. Other researchers extended the eye tracking system to a face tracking system [62]. Therefore, eye tracking became a part of the overall fatigue monitoring system. Since the face tracking system monitored larger areas, the results might be more robust and more reliable; however, more complicated algorisms and more computing resources are required.

2.2.4 Physiological indicators

Physiological measurements, such as electroencephalography (EEG) and electrocardiography (ECG), reflect human status, and have been used as fatigue indicators. Electroencephalography reflects brain activities, and electrocardiography represents heart activities. Both measurements reveal human physiological status, which may change as a response to external stimulation.

2.2.4.1 EEG

Among the psychophysiological parameters that have been used as fatigue indicators, electroencephalography (EEG) perhaps is the most promising method [8]. The electroencephalograph is a recording of the electrical activity of the brain, usually obtained by means of electrodes placed on the scalp. The graphic recording obtained is called an electroencephalogram, which is used to study brain waves. Brain activity is graphically reflected by EEG; therefore, the EEG signal has been widely employed to study brain activity in the transition period from wakefulness to the onset of sleep [13, 27, 63-66]. Many driver fatigue related studies used EEG to investigate fatigue levels of the driver. One traditional method is to assess driver alertness/fatigue based on the EEG power spectrum analysis [63, 67-72]. A close and strong relationship between changes in driving performance and the EEG power spectrum was demonstrated [63], and only requires two channels of EEG signals. Estimation/prediction data from the EEG based model match well with each of the actual driving performance measures. This study suggested that it was feasible to accurately estimate driving errors based on multi-channel EEG power spectrum estimation and principal component analysis. While these studies only employed EEG as a fatigue indicator, some other studies combined EEG with additional fatigue estimators (such as heart rate variation, blood pressure, etc.) [66, 73-76].

While EEG power spectrum analysis was popularly used to estimate driver fatigue, various entropy measures of the EEG signal were considered by other researchers as fatigue indicators [13]. These parameters were (1) relative α band energy, (2) Shannon Entropy, (3) Renyi Entropy of order 2 and order 3, (4) $(\alpha+\beta)/\delta$ ratio. The results indicate Shannon Entropy and Renyi Entropy provide a good estimation of different fatigue levels. It was concluded that fatigue indicating parameters based on higher order entropy measures of EEG signal in the wavelet domain can be used to quantify the level of fatigue in human drivers or human operators in critical safety human-machine interactions [13].

In another recent study, four ratios of slow wave to fast wave have been suggested as fatigue indicators [77]. These four ratios were calculated based on the power spectrum of delta, theta, alpha, and beta components. It was reported that all these ratios showed increase over time and could be implicated for detecting fatigue changes. These four measurements were (1) the ratio of the theta spectrum over beta spectrum, θ/β, (2) the ratio of the alpha spectrum over beta spectrum, α/β, (3) the ratio of the summation of theta and alpha spectrum over beta spectrum, $(\theta + \alpha)/\beta$, and (4) the ratio of the summation of theta and alpha spectrum over the summation of beta and alpha spectrum, $(\theta + \alpha)/(\beta + \alpha)$.

2.2.4.2 ECG

Another physiological variable, heart rate, also varies with different activities of people and can be graphically quantified by Electrocardiography (ECG) [78, 79]. ECG has been frequently used in clinical research, as well as in research associated with fatigue. Heart rate decreases during prolonged night driving, accompanying driver fatigue. This was observed by some researchers who suggested that heart rate change had the potential for indicating driver fatigue [8]. Experiments were conducted to investigate effects of different vibration frequencies on heart rate variability and driving fatigue. The results showed significant differences in all indices of heart rate variability between any two groups during experiment periods, but no significant difference was observed during the pre-experiment period. Subjective fatigue was lowest for the group who drove without vibration and highest for the group who drove with higher vibration frequency. Severity of fatigue symptoms was found to increase with high vibration frequency. This result suggested that driver fatigue ratings were associated with higher vibration frequencies in simulated driving. It also showed that different vibration frequencies resulted in different autonomic nerve activities. Other researchers [78] investigated low frequency (LF) and high frequency (HF) components of heart rate variability (HRV) and fatigue effects to assess HRV as an indicator of driver fatigue. It was shown that the LF/HF ratio was significantly lower during fatigue as compared to the alert state. It was also observed that the accuracy of the neural network, which was trained to predict driver fatigue level using HRV, was very high at 90% and the error reduced to minimum and the output converged to the desired results. This study confirmed that HRV can be used as an indicator of fatigue. The LF/HF ratio decreases as fatigue increases, while driving performance declined.

In a recently developed driver fatigue recognition system, ECG and EEG were considered as important factors for inferring the online driver fatigue level [80]. To estimate the driver fatigue level, contextual variables (sleeping quality, circadian rhythm, and work environment), observable variables (eye movement, EEG, and ECG), and hidden variables (driver fatigue/alertness level) were used to construct the Dynamic Bayesian network. By using multiple contextual and physiological features, the system was able to predict driver fatigue. The researcher suggested that a more reliable and accurate driver fatigue prediction could be obtained by including more contact physiological features. It was also suggested that ECG and EEG were two important components in this fatigue predicting model. The study showed that the model lost accuracy significantly when the EEG and ECG were removed from the model.

2.3 Driving performance

Driving performance reflects the driver ability to control the vehicle, and is essential to road safety. Driving performance can be measured by different parameters.

These parameters can be categorized into three groups, which will be described in this section.

The first group was related to steering wheel control, including steering wheel angle input (SA), steering wheel rate (SR), and vehicle yaw rate (YR). Steering wheel angle input recorded instantaneous angular position of the steering wheel. Steering wheel rate was the time derivative of the steering wheel angle. Vehicle yaw rate recorded the rate of change in heading angles of the vehicle. Steering wheel movement (steering wheel angle and frequency) has been examined in monotonous and complex road scenarios [81]. The result showed that more frequent large steering turns indicated greater decrements in driving performance and increased fatigue levels in the more monotonous road scenario. Another recent study investigating the relationship between steering wheel angle and driver fatigue, which is estimated by EEG, indicated that steering wheel angle was an effective indicator of driver fatigue [31].

The second group was related to lateral position control, including lateral position (LP) and lateral velocity (LV). A lane-keeping task has been used to estimate driving performance and identify driver state by some researchers [51, 81]. In this study, lateral position was defined as the distance between the center line of the vehicle and the center of the current lane. At the beginning of each driving session, the simulator initially set the lateral position to zero. Lateral velocity was the time derivative of lateral position. Lateral position is an important estimation of driving performance, because it measures the ability of the driver to maintain the safe distance to the road users on the conjugate lanes. In general, the smaller of the mean value and standard deviation of the lane position, the better driving performance. When drivers are highly alert and able to concentrate, they can detect a very small deviation of the vehicle from the center of the lane, and can quickly respond to this deviation by adjusting the steering wheel to avoid propagation in this deviation. Trying to keep the vehicle at the center of the lane, the mean of the lane position is usually close to zero. Therefore, the mean and standard deviation of the lane position are both small when the driver is not fatigued. After prolonged driving tasks, drivers may get less alert and have difficulty concentrating; they may become less sensitive to deviations of the lane position. Due to slowed information processing speed at a high fatigue level, drivers cannot respond to the deviation as quickly as they do at the low fatigue level. Although the mean of the lane position may remain close zero (suggesting the driver still can drive straight along the lane), the standard deviation may increase, resulting from degraded detecting and slowed responding abilities. At extreme high fatigue levels, the driver may experience micro sleep behind the wheel and lose the ability to control the vehicle. This may result in undesired drifting of the vehicle from one lane to another, which is dangerous. In summary, lateral position is one of the most direct observations of driving performance, which can be affected by driver fatigue and affects road safety. The third group was related to speed control, including longitudinal speed (VE) and acceleration (AC). Speed control directly affects the longitudinal distance between vehicles, and maintaining safe distance is essential to avoid tailgating.

These eight driving performances are listed in Table 1. Detailed descriptions of the parameters are provided in the second column, and the units are also included in the third column. The means and standard deviations (SDs) of these driving performances

Table 1. Driving Performance Parameters

Variables	**Description and/or Function**	**Units**
	Steering wheel control	
Steering wheel angle input	Angular position of the steering wheel (SA)	[degree] or [radians]
Steering wheel rate	Estimates driver ability to control the steering wheel (SR)	[radians/second] or [degree/second]
Yaw Rate	Estimate the rate of change in heading angles of the vehicle (YR)	[radians/second] or [degree/second]
	Lateral position control	
Lateral position	Distance between center of the vehicle and the lane center, this parameter represents driver's ability to keep vehicle at the center of the lane (LP)	[feet] or [m]
Lateral velocity	Derivative of the lateral position, this parameter represents variance in driver's ability to keep vehicle at the center of the lane (LV)	[feet/second] or [m/second]
Lateral acceleration	2nd derivative of the lateral position, also represents variance in driver's ability to keep vehicle at the center of the lane (LA)	[feet/second^2] or [m/second^2]
	Speed control	
Longitudinal velocity	Time derivative of the longitudinal position, this represents how fast the vehicle is traveling (VE)	[feet/second] or [km/hour]
Longitudinal acceleration	Time derivative of longitudinal velocity, this parameter represents driver's ability to keep speed of the vehicle constant (AC)	[feet/second^2] or [m/second^2]

can be obtained to examine the state of the driver. Therefore, sixteen parameters related to driving performance are available in driver fatigue assessment. Only data collected during the lane keeping tasks will be used for the analysis of driving performance.

2.4 Driver fatigue countermeasures

With better understanding of driver fatigue mechanisms, how to counter fatigue while driving should be taken into consideration. It is important for researchers to provide helpful advice for drivers on how to avoid/reduce accidents caused by accumulated fatigue. This has led to interest by researchers in studying various fatigue countermeasures. However, the term "fatigue countermeasure" is not well/clearly defined, like the term "fatigue", but in a different way. Although, in the current study, "fatigue" is used to describe a state of people in which physical and/or mental efforts are not desired and operational performance is impaired, there is no common agreement of the definition of "fatigue" [8]. This is due to its complex symptoms, relatively wide range of transitional stages, various individual differences, and diverse causes. On the other hand, "fatigue countermeasure" has been used to describe either of the following two terms:

(1) Any system or device which can help a driver to detect and react to fatigue symptoms [82], or
(2) Any fatigue coping method which provides stimulation to people and invigorates the body and/or mind [37]

Some researchers adopted the first definition in their studies [41, 49, 78, 82-84]. Brown suggested a "technological countermeasure system" monitoring driver steering behavior as an in vehicle fatigue detecting assistant system [82]. Lal developed an algorithm to analyze EEG signals, which could be integrated with a "driver fatigue countermeasure" device to monitor off-line/online driver states [83]. Tran et al. also investigated brain activity using EEG signal as a valid "fatigue countermeasure" in fatigue assessment [84]. Patel et al. suggested that heart rate variability could be implemented into "a fatigue countermeasure system" to assess driver fatigue [78].

Some other researchers adopted the second definition in their studies [37, 85-88]. Åkerstedt et al. found that short sleep and a caffeinated drink were the favorite "fatigue countermeasures" during working hours, after a review of some possible fatigue coping methods [85]. Landstrom et al. studied the effectiveness of sound exposure as a "fatigue countermeasure" to wake fatigued drivers up, and obtained consistently positive results [86]. Brice and Smith revealed that caffeine as an effective "fatigue countermeasure" helped subjects improve steering accuracy [87]. Gershon et al. also studied effects of caffeine, but along with a self-paced manual-dexterity/mastication secondary task (shelling and eating sunflower seeds), and found that both "fatigue countermeasures" had positive effects on reducing fatigue [37]. In another experiment, Gershon et al. conducted a survey to investigate sixteen different "fatigue countermeasures" adopted by professional and nonprofessional drivers. It was found that professional drivers handled driving fatigue strategically but nonprofessional drivers only used tactical methods to pass the time and reduce feeling of boredom [88].

Haworth et al. summarized two functions of "fatigue countermeasures": the first function is monitoring fatigue while driving, and the second function is helping the driver in maintaining alertness [89]. It is clear that the first function is associated with the first definition, and the second function is associated with the second definition. To avoid confusing the two, the second definition given by Gershon et al. [37] is adopted in the current study with slight modification: a driver fatigue countermeasure is any fatigue coping method that helps people to maintain alertness, which may include external/environmental and internal stimulation to invigorate the body and/or mind, and fatigue management strategies to avoid proceeding risky tasks at high level of fatigue.

Åkerstedt et al. suggested that fatigue countermeasures would be classified into two groups [85]. The first group includes carefully developed scheduling and home sleep recommendations which affect fatigue levels outside work hours. The second group includes secondary activities (such as intake of caffeine, short break, exercises, etc.), or environmental factors (light, noise, etc.) which can be applied within work hours or during tasks. Fatigue countermeasures in the first group are long term strategies managing overall fatigue level distribution strategically [85].

One of the studies mentioned previously investigated the effectiveness of fatigue management training as fatigue countermeasure [40]. A comprehensive fatigue management training was given to the driver in driver education programs. The results suggested that driver education was useful for fatigue management. On the other hand, fatigue countermeasures in the second group immediately interfere with the current fatigue level, and the effectiveness varies from one method to another [85].

After a review of studies related to fatigue countermeasures being conducted before 1998, Åkerstedt et al. concluded that short break/sleep and caffeinated drinks were the most favorite, and waking noise was a promising method, whereas some other countermeasures (such as light, temperature, food, and activity) might be useful, but further systematic investigation was needed to give conclusions [85]. In the previously mentioned survey, Gershon et al. investigated sixteen different fatigue countermeasures based on 100 professional and 90 nonprofessional drivers [88]. The results revealed that listening to radio and opening the window were the most effective methods that were the most frequently adopted by both groups. Talking to others was the top choice of the nonprofessional group. On the contrary, professional drivers more frequently adopted strategic methods including planning rest stops ahead, taking short breaks, and taking caffeinated drinks [88].

Another study conducted by Gershon et al. compared the effectiveness of two fatigue countermeasures: caffeinated energy drink and a manual-dexterity activity (shelling and eating sunflower seeds) [37]. Caffeinated energy drink showed significant positive benefit in reducing subjective and physiological fatigue measures and driving performance. The manual-dexterity activity helped drivers reduce subjective and physiological fatigue temporarily, but deteriorated driving performance.

Landstrom et al. conducted an on-road experiment to examine effectiveness of waking sound with four different frequencies (2050, 3700, 5800, and 10750 Hz) [45]. The results showed that with waking sound, the alertness of the driver was significantly increased. The waking sound also had positive impact on road safety. Another simulated driving study revealed that hitting a rumble strip increased driver alertness for a short time period [46]. This is because hitting a rumble strip provided a warning signal which combines sound and vibration stimulations. Other than the monotonous auditory stimulation, music provides more variable auditory stimulation with various rhythms and mood effects. According to a recent study, physiological arousal was inhibited and driving performance was improved more effectively during high-demand driving tasks, when abrupt music changes were applied, compared to gradual music changes [90].

It is interesting that a type of vibrating seat has been available in the market, providing an alarming signal to wake a fatigued driver up. However, whether vibration should be considered as an alarming device or fatigue countermeasure device is still questionable. One researcher conducted an experiment to study the effect of different vibration frequencies on drivers [79]. The results revealed that both low frequency (1.8Hz) and high frequency (6Hz) vibration induced more fatigue after prolonged simulated driving, compared to the control driving group who completed the same driving task without vibration. From results of this research, a vibrating seat may not be suitable as a fatigue countermeasure, because continuous vibration may make a driver more fatigued, instead of making them more alert. On the other hand, a sudden activation of a vibrating seat may provide temporary alerting/warning effects, which is similar to that of hitting rumble strips on the road. If warning systems are to be examined, the vibrating seat can be introduced into the experiment.

Some of the fatigue countermeasures that have been studied in the previously mentioned studies are listed in Table 2. Some other fatigue countermeasures may be adopted by drivers (for example, chewing gums, rubbing eyes, shaking head, etc.), but very few people reported these were effective. An individual may have his/her personal preference while choosing the fatigue countermeasure. However, it is important to notice

Table 2. List of fatigue countermeasures

1. Stop for short nap
2. Opening the window
3. Listening to the radio/music
4. Drinking coffee
5. Drinking energy drink
6. Shelling and eating sunflower seeds
7. Smoking
8. Talking on the cellular phone
9. Eating salty snacks
10. Eating chocolate snacks
11. Talking with passenger
12. Driving barefoot
13. Stopping for exercise
14. Change seating position
15. Watching the view
16. Thinking personal thoughts
17. Increased light stimulation
18. Waking sound
19. Hitting rumble strip

that with different types of fatigue, different fatigue countermeasures should be adopted to effectively avoid operational errors. A recent study suggested that the causes of sleep-related driver fatigue and task-related fatigue were different, therefore, different countermeasures were necessary [41]. In general, sleep-related fatigue can only be recovered by taking sufficient rest. For task-related fatigue, depending on mental overload or under-load, different technologies can be adopted. With mental overload task-related fatigue, automation technologies (such as the lane-keeping assistant system) can be activated to reduce mental workload; therefore, allowing the driver recover from fatigue. With mental under-load task-related fatigue, interactive technologies (such as the waking sound system) may help the driver maintain necessary level of activity and alertness.

Although various fatigue countermeasures have been adopted, consuming caffeine and listening to music are two of the most frequently adopted, which are also believed to be the most effective. To date, there has been no study investigating the effects of and differences between these two. One objective of this study is to compare the two fatigue countermeasures: consuming caffeine and listening to music. Variations in subjective fatigue levels and deterioration of driving performance are investigated to examine the effects of and differences between the two methods.

Chapter 3 Development of Subjective Driver Fatigue Score

A Subjective Driver Fatigue Score (SDFS) will be described in this chapter. The SDFS has been specially developed to quantitatively estimate driver states. It is attempted to examine severity of various fatigue symptoms developed during driving, evaluate the reserve driver capacity, etc. Several existing questionnaires were first reviewed, and then some of the items (questions) from these questionnaires were carefully chosen for the SDFS. Finally, several additional items were created to form the completed questionnaire.

3.1 Literature review

3.1.1 Subjective assessment

Subjective assessment has been widely employed in many areas as psychological parameters. For example, one famous questionnaire is the McGill Pain Questionnaire, which has been developed to examine properties of clinical pain [91]. This sophisticated pain rating tool helps the patient in describing pain location, pain intensity, etc. at the present. Because the McGill Pain Questionnaire usually takes 5 – 10 minutes for the patient to complete, which is relatively long and inconvenient for some studies, a short version has been developed to replace the full questionnaire in certain circumstances [92]. This short version, developed based on the full version, takes only 2 – 5 minutes to administer. Another pain rating tool, the Wong-Baker Faces Rating Scale, combines cartoon faces, numbers, and words together to form a unique pain evaluating method [93]. These alternative pain assessment scales provide diagnostic tools allowing patients to explain the severity and quality of pain experienced to the clinic professional.

Subjective assessment is also often used to estimate workload. The NASA – Task Load Index is one of the most widely used multi-dimensional rating scales to estimate workload, combining the magnitude and sources of six workload-related factors (mental demand, physical demand, temporal demand, performance, effort, and frustration) [94]. For example, in a simulated driving experiment, the NASA – Task Load Index was employed to examine the diurnal pattern of subjective workload [29]. In another experiment, the NASA – Task Load Index was used to estimate differences in subjective workload between left-turn and straight driving. In the same experiment, the USAF subjective workload assessment technique was also used to examine variation in subjective workload [95]. Recently, some researchers attempted to objectively assess workload using eye tracking systems, but subjective workload was employed as an independent variable [59]. While mental workload was estimated subjectively in the previous experiments, physical workload was evaluated subjectively in another experiment focusing on low back and trapezius muscle activity in bus drivers [74]. Various questionnaires or scales have been developed and employed in different areas to observe mental/physical workload.

Another important application area of subjective assessment is studies in sleepiness. For example, the Epworth Sleepiness Scale (ESS) has been developed to measure the general level of daytime sleepiness of the patient [27]. It has been concluded that Epworth Sleepiness Scale scores were highly correlated with the results obtained from the multiple sleep latency test and overnight polysomnography, which is considered as a valid method providing assessment of sleepiness of the patient with a sleep disorder. While developing and examining the Epworth Sleepiness Scale, the other two subjective sleepiness scales, the Stanford Sleepiness Scale (SSS) and the Visual Analogue Scale (VAS) of sleepiness were used as references. However, the SSS and VAS of sleepiness are not suitable for diagnosing the sleep disorder, because (1) both tests examine levels of sleepiness and symptoms/feelings at the moment when the test is taking, and (2) the results of the subjective assessment of both tests are not correlated with the result of the multiple sleep latency test and overnight polysomnography [27]. On the other hand, the SSS, in spite of its shortage in diagnosing sleep disorders, has been widely used in studies associated with attention, fatigue, etc. [13, 19, 28, 35]. In studies, the SSS was the only subjective assessment [28]; in some other studies, the SSS was used along with additional questionnaires, such as the Epworth Sleepiness Scale, the VAS, or the Piper Fatigue Scale [13, 19, 35]. In the studies discussed above, the subjective sleepiness scales have been frequently used as fatigue indicators, because fatigue is closely associated with sleepiness in many cases.

Subjective assessment is one of the most important fatigue indicators, as discussed in the previous chapter. Although some subjective sleepiness scales discussed in the previous paragraph have been used to assess fatigue [13, 28, 35]; researchers have developed questionnaires to subjectively measure fatigue levels, examples including Pearson's 13-item Fatigue Checklist developed in 1957 [42], Chalder's 11-item fatigue scale developed in 1993 [11], and Michielsen's 10-item Fatigue Assessment Scale developed in 2004 [96]. The thirteen items of Pearson's Fatigue Checklist were carefully examined and selected from approximately five hundred items, attempting to determine fatigue levels in industrial studies, for example, in determining working hours, planning resting schedule, improving working conditions, etc. [42]. The fatigue scales of Chalder et al. and Michielsen et al. were developed for clinical studies, to diagnose disease, investigate effectiveness of medical treatments, etc. [11, 96]. However, studies in fatigue are not limited to industrial and clinical areas. For example, it is also important to understand and manage fatigue in athletics and in the military.

In the following section 3.1.2, various subjective assessment tools are to be reviewed first. Then, some of previously developed subjective fatigue assessment questionnaires are examined. A summary literature review is given in section 3.1.3. In section 3.2, the details of the Subjective Driver Fatigue Scale are introduced.

3.1.2. Subjective fatigue assessment

Although, studies in fatigue can be traced back to at least 90 years ago [14], recent researchers still have difficulty in agreement into a generally accepted definition of fatigue [8, 11]. In an early study, it was thought that fatigue was caused by repeating an activity and the capacity for repeating it was diminished [14]. Some researchers defined fatigue as states at which efficiencies were reduced and efforts were not desired [6, 12]. Some others defined fatigue as a subjective symptom felt by individuals accompanying interfered capacities to function normally [17]. There are also some researchers who believe that fatigue indicates the effects of being unable to maintain a desired level of performance on a task, because of working overtime or insufficient rest, and the term fatigue can be used interchangeably with the term sleepiness [16]. The variety of definitions of the term fatigue is primarily caused by various uses of the concept in different areas, including industry, clinic/medic, military, etc. in which subjects experience similar but different fatigue conditions. Despite the variety in definition, most researchers agree that fatigue can be classified in physical fatigue and mental fatigue. Physical fatigue is also referred to as muscle fatigue, accompanied by increases in lactic acid and carbon dioxide in the muscular tissue and resulting acidic muscle, reduced power, slowed movement, etc.. Mental fatigue is a psychological phenomenon, accompanied by symptoms such as disinclination of effort and reduced efficiency/alertness. While physical fatigue can be easily identified; mental fatigue can hardly be self-recognized on the onset. Ignorance of the onset of mental fatigue could result in serious human errors while performing risky tasks. Therefore, various subjective and more objective fatigue indicators have been developed, as discussed in Chapter 2. In the rest of this section, subjective fatigue assessment will be further discussed in detail.

3.1.2.1 Fatigue subjective assessment in clinical or medical practice

Fatigue is a common symptom of many diseases and has important impacts on individuals in certain physical conditions (pregnancy, infections, etc.); and it may result from the use of medication or medical treatment (chemotherapy, physical-therapy, radiotherapy, etc.) [96]. Various fatigue scales have been developed to identify severity of fatigue for the patient in the clinic. An early 14-item Fatigue Scale (FS) consists of physical and mental symptoms [11]. Each item was assigned to four descriptions: "better than usual", "not more than usual", "worse than usual", and "much worse than usual," which may also be replaced by a "Likert score" for weight calculation. The fourteen items of the scale are listed in Table 3. While this scale distinguishes fatigue into two parts, another 20-item Multidimensional Fatigue Inventory (MFI) covers five dimensions: general fatigue, physical fatigue, mental fatigue, reduced motivation, and reduced activity. Each of the twenty items was weighted using a 7-point scale, with higher scores indicating higher degree of fatigue [43]. A part of the MFI is listed in Table 4. Another multidimensional fatigue scale is the Piper Fatigue Scale (PFS), which has been widely employed in medical practice. PFS includes twenty-two items which distinguishes into four dimensions: behavioral/severity, affective meaning, sensory, and cognitive/mood [97]. These items are listed in Table 5. Each item is scored using a "Likert score" (ranging from 0 to 10, with 10 being the most severe). Four subscale scores are calculated by averaging the items under each of the subscales; a total fatigue score then can be calculated by taking the mean value of the four subscale scores. A more recently developed subjective fatigue assessment tool, the Fatigue Assessment Scale (FAS), has been constructed by combining items selected from four existing fatigue scales: the Checklist Individual Strength—20 (CIS-20), the Emotional Exhaustion subscale from the Maslach Burnout Inventory (MBI), the Energy and Fatigue subscale from the World Health Organization Quality of Life assessment instrument (WHOQOL), and the Fatigue

Scale (FS). This fatigue scale includes ten items and is unindimensional [96]. For each item, one of five answers (1=Never, 2=Sometimes, 3=Regularly, 4=Often, and 5=Always) can be chosen to indicate the usual feeling.

Table 3 14-item Fatigue Scale
Physical symptoms 1. Do you have problems with tiredness? 2. Do you need to rest more? 3. Do you feel sleepy or drowsy? 4. Do you have problems starting things? 5. Do you start things without difficulty but get weak as you go on? 6. Are you lacking in energy? 7. Do you have less strength in your muscles? 8. Do you feel weak?
Mental symptoms 9. Do you have difficulty concentrating? 10. Do you have problems thinking clearly? 11. Do you make slips of the tongue when speaking? 12. Do you find it more difficult to find the correct word? 13. How is your memory? 14. Have you lost interest I n the things you used to do?
Four options were used “better than usual”, “not more than usual”, worse than usual”, “much worse than usual”[11].

Table 4 20-item Multidimensional Fatigue Inventory	
1. I feel fit	Yes, that is true |1 |2 |3 |4 |5 |6 |7 | no, that is not true
2. Physically I feel only able to do a little	Yes, that is true |1 |2 |3 |4 |5 |6 |7 | no, that is not true
3. I feel very active	Yes, that is true |1 |2 |3 |4 |5 |6 |7 | no, that is not true
4. I am not up to much	Yes, that is true |1 |2 |3 |4 |5 |6 |7 | no, that is not true
5. Thinking requires effort	Yes, that is true |1 |2 |3 |4 |5 |6 |7 | no, that is not true
A part of the MFI form [43], 7-point Likert scale is used, with higher scores indicating higher degree of fatigue	

Table 5 22-item Piper Fatigue Scale
Behavioral/severity 1. Fatigue distress 2. Interference with daily activities 3. Interference with socializing 4. Interference with sexual activity 5. Overall interference with enjoyable activities 6. Fatigue intensity/severity
Affective meaning 7. Pleasant—unpleasant 8. Agreeable—disagreeable 9. Protective—destructive 10. Positive—negative 11. Normal—abnormal
Sensory 12. Strong—weak 13. Awake—sleepy 14. Lively—listless 15. Refreshed—tired 16. Energetic--unenergetic
Cognitive/mood 17. Patient—impatient 18. Relaxed—tense 19. Exhilarated—depressed 20. Able to concentrate—unable to concentrate 21. Able to remember—unable to remember 22. Able to think clearly—unable to think clearly
All items are coded on a 0-10 numeric scale. To calculate subscale scores, the scores on all items within the particular subscale are added, and this sum is then divided by the number of items within the particular subscale. This gives a mean subscale score for the subject form 0-10 (minimal-maximal fatigue). A total fatigue score can be calculated by adding the four subscale scores and dividing this sum by four [97].

The whole scale is listed in Table 6. These four fatigue assessment tools have been developed for clinical or medical practice. Apparently, the 14-item FS and 10-item

FAS examine symptoms of the patient within a time period, while the MFI and PFS examine symptoms at the moment when examination is taken.

Table 6 10-item Fatigue Assessment Scale (FAS)
1. I am bothered by fatigue (WHOQOL) 2. I get tired very quickly (CIS) 3. I don't do much during the day (CIS) 4. I have enough energy for everyday life (WHOQOL) 5. Physically, I feel exhausted (CIS) 6. I have problems starting things (FS) 7. I have problems thinking clearly (FS) 8. I feel no desire to do anything (CIS) 9. Mentally, I feel exhausted 10. When I am doing something, I can concentrate quite well (CIS)
The ten statements refer to how individuals usually feel, and one of the five answers provides corresponding score as follows: 1=Never, 2=Sometimes, 3=Regularly, 4=Often, and 5=Always [96].

3.1.2.2 Fatigue subjective assessment in military

Another important application of subjective fatigue assessment is in military settings, because of high levels of workload and the extreme harsh environment experienced by operators, who usually are required to control complex machines such as aircrafts and tanks. As early as 1957, two equivalent fatigue checklists were developed to measure fatigue levels of airmen [42]. Each of the items from the two equivalent fatigue checklists was weighted by choosing one of three descriptive answers ("worse than", "same as", and "better than"), which were assigned numerical values (0,1,and 2) [42]. The items of the checklists were carefully chosen from approximately 500 items, and each checklist was valid in providing a unidimensional fatigue indicator. This early subjective fatigue assessment tool helped managers in scheduling, studying working environment/conditions, ergonomic equipment design, etc. to maintain desired output from operators. The two equivalent fatigue checklists are listed in Table 7. On the other hand, the developer of the checklists suggested that the results obtained from this subjective fatigue assessment tool should not be used to predict performance of the subjects being tested [42]. Although many fatigue related studies were conducted in medical practice and warfighting, fatigue was initially studied in industry [14, 17].

Table 7 Two equivalent13-item Fatigue Checklist

A	B
1. Like I am busting with energy	1. I never felt fresher
2. Extremely peppy	2. Extremely lively
3. Very lively	3. Very fresh
4. Very refreshed	4. Very rested
5. Quite fresh	5. Quite fresh
6. Somewhat fresh	6. Somewhat refreshed
7. Slightly tired	7. A little tired
8. Slightly pooped	8. A little pooped
9. Fairly well pooped	9. Fairly pooped
10. Petered out	10. Awfully tired
11. Very tired	11. Tuckered out
12. Extremely tired	12. Weary to the bone
13. Ready to drop	13. Dead tired

Each item is weighted as follows: 0=worse than, 1=same as, and 2=better than [42].

3.1.2.3 Fatigue subjective assessment in industry

Fatigue was initially studied during the First World War to investigate the relationship between fatigue and productivity efficiency of the workers in industry [17]. Many fatigue tests have been proposed since then, but subjective fatigue assessment was not an option when researchers discussed whether fatigue can be measured or not [14].

However, questionnaires with various complexities have been developed and successfully used to measure fatigue levels in industrial environments. One of these questionnaires is listed in Table 8. Each item includes two opposing and mutually exclusive words/phrases and a scalar bar, which nowadays is called the Visual Analog Scale, to quantify the subjective feeling at that particular moment [12]. This subjective fatigue assessment tool is simple and easy to use. It is usually administered at the beginning and end of an experiment and the differences between the measurements suggest the changes in fatigue levels of the subject.

Table 8 Questionnaire with VAS For Industry Use

1.	Fresh	|--|	Weary
2.	Sleepy	|--|	Wide awake
3.	Vigorous	|--|	Exhausted
4.	Weak	|--|	Strong
5.	Energetic	|--|	Apathetic
6.	Dull, indifferent	|--|	Ready for action
7.	Interested	|--|	Bored
8.	Attentive	|--|	Absent-minded

VAS is used for each item to determine fatigue levels [12]

Many similar questionnaires have been developed in industry for its own studies, but with various complexities for different purposes [12]. Some questionnaires were used for a quick check of the fatigue level at the moment in operating processes; some others were used for examining characteristics of fatigue experienced by the subject in certain industrial environments. However, there were fatigue related studies that employed subjective assessment questionnaires from other areas (such as sleepiness scales). For example, in a recent study focusing on the needs of the mining industry, the Karolinska Sleepiness Scale (KSS) was used as a subjective fatigue measure [23]. Actually, in many cases, the terms sleepiness and fatigue are used interchangeably, and in these cases it can be classified as sleep-related fatigue as described by May et al. [41]. Therefore, it is no surprise that sleepiness scales, such as the KSS and SSS, have been used as subjective fatigue assessment tools in these studies.

3.1.2.4 Fatigue subjective assessment in driving

Fatigue studies in the transportation industry have been pursued for decades, to investigate the impact of fatigue on operators such as pilots, train-operators, bus-drivers, heavy-truck-drivers, etc. [20, 69, 74, 89]. Although operators experience various working environments while controlling different transportation devices, they share similar operational characteristics. Basic operation requires (1) observation of traffic condition in front of and around the transportation devices, (2) manipulation of the device to control direction, speed, etc. according to traffic conditions (3) communication with others, and (4) preparation for any unanticipated events/incidents. Therefore, the operator is under high stress levels and fatigue has important impacts on performance, which is essential to the safety of the people involved. In this study, road drivers are of interest and subjective assessment in driver fatigue is one of the focuses of this study.

Some of the subjective assessment tools discussed in previous sections have been used in driver fatigue related studies. Among these, the SSS is probably one of the most widely used tools in driver fatigue measurement, although it has been designed to measure sleepiness. Some researchers used the SSS as the only subjective fatigue measure [28], and some others used the SSS along with other tools. A 3-item VAS was combined with the SSS to examine subjective fatigue level in a real road test [35]. In another study, a set of items were selected from the SSS, PFS, and ESS to measure subjective fatigue levels [13]. The ESS is originally designed to examine sleepiness, which is similar to the SSS. The PFS, on the other hand, is usually used for medical practice, as described previously. Another fatigue indicator developed for medical practice, the 14-item FS listed in Table 3, has also been used in a driver fatigue study [68]. In a driver fatigue study, it is reasonable to use the subjective fatigue assessment tools developed in other areas, as described previously, because fatigued individuals share some common characteristics. These characteristics include severe tiredness, low motivation, etc. which are described in the definition of fatigue. The sleepiness scales also showed good results in application to driver fatigue studies, because usually fatigued individuals feel sleepy and low motivation. Moreover, some researchers used the terms fatigue and sleepiness interchangeably [16].

3.1.3 Summary of literature review

While researchers have developed subjective assessment tools in many areas, including fatigue indicators for medical practice, industrial study, military application etc., to our best knowledge, very few researchers have developed a subjective fatigue indicator for drivers. The literature review in the previous sections revealed that most studies related to driver fatigue have employed subjective assessment tools from other areas. However, strictly speaking, none of the subjective assessment tools described in previous sections fully reflects the characteristics of driver fatigue. For example, sleepiness scales usually do not include physical/muscular fatigue symptoms (such as tired back, sore feet, etc.), but physical fatigue symptoms have an important impact on drivers and their driving performance. Subjective fatigue scales for medical practices usually include some special items relating to particular diseases, but drivers who operate vehicles are usually healthy, and these disease-related items may not be able to apply to healthy drivers. All other subjective assessment tools have been developed for certain professional applications, according to the required parameters and environment experienced by the subjects. Therefore, it is necessary to develop a subjective driver fatigue scale to measure fatigue levels of drivers.

3.2 Development of SDFS

In this section, the description is given of a questionnaire specially developed for driver fatigue. Then a scale is described to show how to quantitatively estimate driver fatigue using the questionnaire.

3.2.1 Questionnaire for driver fatigue

To estimate subjective fatigue levels of drivers, a questionnaire has been developed. The questionnaire should (1) be distinct from those subjective assessment tools used in other study areas (studies in sleepiness, for example), (2) be able to describe fatigue symptom development during driving tasks, (3) be easy to understand and administer, (4) be free of ambiguities, and (5) be not only "sufficient" but also "concise" ("sufficient" means the questionnaire contains enough items to estimate all aspects of driver fatigue; "concise" means the questionnaire is short enough to allow the subject to complete it within a limited time period). Since all fatigued individuals share some common characteristics, some items reflecting these common driver fatigue symptoms can be selected from existing fatigue scales. For example, some items from existing sleepiness scales may also reflect driver fatigue characteristics, thus, can be included in the questionnaire. On the other hand, driver fatigue has its unique characteristics (changes in driving behavior, for example). These unique characteristics of driver fatigue (for example, desirability to pass a leading vehicle) need specially designed items to reflect their severity. A questionnaire has been developed, including twenty-six items. Twenty of the items were selected from sleepiness scales and fatigue scales discussed in the previous sections, and the other six were generated to reflect specific fatigue characteristics of drivers. The items are listed in Table 9.

To obtain a quantitative assessment of driver fatigue, a Likert score is used to give a numerical answer to each item, except the last one. The answer to the last question is a reasonable positive number, indicating how many hours the driver can keep driving from the moment when the question being presented.

A pilot study showed that all the five requirements (described at the beginning of the section) have been met, except that it took 5 to 10 minutes for the subject to complete the whole questionnaire. It is not concise enough when the questionnaire is used during the driving task. The driver will be distracted while answering the questionnaire, therefore, it is necessary to minimize the time period of distraction. On the other hand, fatigue levels may change significantly after 10 minutes when the subject is severely fatigued. Therefore, modification should be made on the questionnaire listed in Table 9, to meet the fifth requirement (namely, sufficient and concise). After a careful study, the final questionnaire has been reduced to twelve items, some of which were slightly

Table 9 List of items for driver fatigue
Items selected from existing sleepiness/fatigue scales: 1. Are your feet sore (not at all – extremely sore) 2. To what degree your eyes are strained? (not at all – extremely) 3. Are you feeling any backache (not at all – a great deal) 4. How much headaches are you feeling now? (None – a great deal) 5. Are you feeling chill? (not at all – extremely) 6. Are you feeling stiff muscles (not at all – extremely) 7. Are you feeling any numbness? (not at all – extremely) 8. Are you feeling any ear ringing? (not at all – extremely) 9. Are you feeling upset stomach? (not at all – extremely) 10. Are you feeling any dizziness? (not at all – extremely) 11. To what degree are you feeling be able to concentrate (able– unable) 12. To what degree are you feeling be able to think clearly (able – unable) 13. To what degree are you feeling be able to remember (able -- unable) 14. Overall, how much is the fatigue you are feeling now interfering with your ability to engage in the kind of activities you enjoy doing? (None – a great deal) 15. To what degree are you feeling awake (extremely – not at all) 16. To what degree are you feeling drowsy (not at all – extremely) 17. To what degree are you feeling energetic (energetic – unenergetic) 18. To what degree are you feeling relaxed (relaxed – tense) 19. To what degree would you describe the fatigue you are feeling now as being normal/abnormal (normal – abnormal) 20. How much effort do you want make to do a good job? (a great deal – none)
Items specifically generated for driver fatigue 21. To what degree are you going to pass the leading vehicle which is much slower (10km/h e.g.) than your current speed? (pass – not pass) 22. To what degree you are willing to pull over and have a rest? (not at all – want to stop immediately) 23. To what degree is the fatigue you are feeling now interfering with your ability to drive safely? (None – a great deal) 24. To what degree did you recognize your feeling (enjoyable/boring/unpleasant, etc.) about the view along the road during last 10 minutes? (strongly – not recognized) 25. Are your joints stiff? (not at all – extreme) 26. How many hours do you think you can keep driving from now on? (________ hours)
A Likert score is used to estimate severity of each item, except item No.26, the answer of which is a positive number

modified to better represent characteristics of fatigue experienced by drivers. The shortened questionnaire is listed in Table 10, which also includes the Likert score ranging from 1 to 10. The 12-item questionnaire requires only 1 to 3 minutes to administer (in the following two experiments, most subjects can finish the questionnaire within 2 minutes after practice.). The items in the questionnaire also reflect the most important and common aspects of driver fatigue. The feedback from the pilot study showed that the items are easy to understand and have no ambiguity. The Likert score makes the tool very easy to administer. Because some unique items have been developed only for drivers (items 1, 6, 7, and 12), the questionnaire is distinct from other subjective assessment tools (such as the SSS).

Table 10 Driver Fatigue Questionnaire (DFQ)

1.	To what degree is the fatigue you are feeling now interfering with your ability to drive safely?	None — A great deal	1 2 3 4 5 6 7 8 9 10
2.	To what degree are you feeling ……	Awake — Sleepy	1 2 3 4 5 6 7 8 9 10
3.	To what degree are you feeling ……	Able to concentrate — Unable to concentrate	1 2 3 4 5 6 7 8 9 10
4.	If you have a headache now, rate its severity	None — A great deal	1 2 3 4 5 6 7 8 9 10
5.	To what degree are your eyes strained?	None — Very Strained	1 2 3 4 5 6 7 8 9 10
6.	How likely are you to pass a leading vehicle which is much slower than your current speed?	Pass — Not pass	1 2 3 4 5 6 7 8 9 10
7.	To what degree are you willing to pull over and have a rest?	Not at all — Very willing	1 2 3 4 5 6 7 8 9 10
8.	Are your feet sore?	Not at all — Extremely sore	1 2 3 4 5 6 7 8 9 10
9.	Are you feeling any backache?	None — A great deal	1 2 3 4 5 6 7 8 9 10
10.	Are your joints stiff?	Not at all — Extremely stiff	1 2 3 4 5 6 7 8 9 10
11.	Are you feeling any numbness?	None — A great deal	1 2 3 4 5 6 7 8 9 10
12.	How many more hours do you think you can keep driving?	(3) hours	

3.2.2 Calculation of SDFS

One of the major purposes of this study is to develop a subjective assessment tool that can quantitatively estimate fatigue levels of drivers. The numerical answers to the individual items in the Driver Fatigue Questionnaire (DFQ) presented in Table 10 makes it possible. For each item, the subject offers a numerical answer, ranging from 1 to 10. Therefore, for the first eleven items, eleven numerical answers are obtained. The summation of these eleven numerical answers represents the overall fatigue level of the driver at the moment when the questionnaire being administrated. This summation is defined as the Subjective Driver Fatigue Score (SDFS). In the current study, the SDFS of the m^{th} subject at the time t is denoted as ${}_{t}SDFS^{m}$ and can be calculated using Equation 1.

$$ {}_{t}SDFS^{m} = \sum_{n=1}^{11} {}_{t}Q_{n}^{m} \qquad \text{Equation 1} $$

where

${}_{t}\mathrm{SDFS}^{\mathrm{m}}$ = overall fatigue level of $\mathrm{m^{th}}$ subject at the time t

${}_{t}\mathrm{Q}_{\mathrm{n}}^{\mathrm{m}}$ = the score of the $\mathrm{n^{th}}$ item in the questionnaire for $\mathrm{m^{th}}$ subject at the time t, and $1 \leq \mathrm{n} \leq 11$

For example, the highlighted numbers in Table 10 are answers to the twelve items in the questionnaire administered by the 8^{th} subject at time $t = 0$; then the overall fatigue level of this subject at the beginning of the driving session can be calculated using Equation 1, shown as follows:

given:

$${}_{0}\mathrm{Q}_{1}^{8} = 3; \quad {}_{0}\mathrm{Q}_{2}^{8} = 7; \quad {}_{0}\mathrm{Q}_{3}^{8} = 5; \quad {}_{0}\mathrm{Q}_{4}^{8} = 1;$$

$${}_{0}\mathrm{Q}_{5}^{8} = 1; \quad {}_{0}\mathrm{Q}_{6}^{8} = 10; \quad {}_{0}\mathrm{Q}_{7}^{8} = 4; \quad {}_{0}\mathrm{Q}_{8}^{8} = 4;$$

$${}_{0}\mathrm{Q}_{9}^{8} = 4; \quad {}_{0}\mathrm{Q}_{10}^{8} = 1; \quad {}_{0}\mathrm{Q}_{11}^{8} = 1; \quad {}_{0}\mathrm{Q}_{12}^{8} = 3;$$

then:

$${}_{0}SDFS^{8} = \sum_{n=1}^{11} {}_{0}Q_{n}^{8} = 3 + 7 + \cdots + 1 + 1 = 41$$

The last item in the questionnaire, denoted as ${}_{t}\mathrm{Q}_{12}^{\mathrm{m}}$, represents residual driver capacity, which is expected to decrease with the increase in SDFS.

It can be seen that for each item, the possible minimum value is 1 and maximum value is 10, thus, SDFS has a possible minimum value of 11 and a maximum value of 110. Larger values of SDFS represent higher levels of driver fatigue. Therefore, the subjective fatigue assessment tool includes two parts. The first part is the 12-item questionnaire; and the second part is the numeric subjective driver fatigue indicator including (1) the overall driver fatigue level denoted as ${}_{t}SDFS^{m}$ and (2) residual driver capacity denoted as ${}_{t}\mathrm{Q}_{12}^{\mathrm{m}}$.

In the following experiments, this subjective fatigue assessment tool will be used and examined for its validity.

Chapter 4 Experiment Design

This study is to investigate the influence of driver fatigue on driving performance and effectiveness of driver fatigue countermeasures (namely, taking a caffeinated drink and listening to music). Two experiments have been conducted, in both of which a computerized driving simulator has been employed.

The first experiment investigated variations in subjective driver fatigue and driving performance during prolonged driving tasks. Each subject completed three 45-minute driving sessions. The subjective driver states were estimated using the questionnaire included in Table 10, and fatigue levels were quantified using the SDFS described in Chapter 3. The SSS was also obtained from the subjects to compare with the SDFS. Sixteen parameters, including means and standard deviations of steering wheel angle input, lateral position, etc. which were listed in Table 1, were used to represent driving performance. Reaction times obtained from Divided Attention Tests were also recorded for comparison. A co-relationship between the SDFS and driving performance was also investigated.

The second experiment investigated the effects of two fatigue countermeasures, intake of caffeine and listening to music, during prolonged driving tasks. Each subject completed three 120-minute driving sessions. The three sessions were control session, caffeine session, and music session. Similar to the first experiment, the SDFS was used for subjective fatigue estimation and sixteen driving performance parameters listed in Table 1 were used for driving performance measurement. Time variations and inter-session variations in the SDFS and driving performance were investigated. In addition, EEG signals were recorded to examine the possibility of using EEG as a driver fatigue online monitoring indicator.

The details of experiment designs and setups are described in the rest of this chapter.

4.1 The 1st experiment

The first experiment investigated how subjective driver fatigue estimated by the SDFS changed with prolonged driving, and how this variation in driver fatigue affected driving performance. As mentioned in the previous literature review (section 3.2), although various questionnaires, such as the SSS and MFI, have been used in fatigue related studies, to date there has been no published questionnaire that has been specifically developed to quantify driver fatigue. Hence the questionnaire described in Chapter 3 and the SDFS calculated based on this questionnaire have been employed, attempting to quantify driver status in the prolonged driving task, during which increases in driver fatigue were expected. Driving performance was recorded and analyzed to examine its possible relation to the SDFS. Reaction time was examined by performing Divided Attention Tasks. Details of the experiment setup are included in this section.

4.1.1 Subjects

To determine the number of subjects, a pilot study has been conducted, with fourteen subjects completing three 45-minute driving sessions (the full experimental procedure is described in section 4.1.2). Power analysis has been used to determine the minimum number of subjects required [98, 99]. Based on the pilot experiment, the mean of the subjective driver fatigue score at the beginning of the experiment is 25.36, with standard deviation of 9.80; the mean of the subjective driver fatigue score at the end of the experiment is 52.93, with standard deviation of 26.16. The absolute mean difference is 27.57 ($|\delta| = |\mu_1 - \mu_2| = |25.36 - 52.93| = 27.57$). Using $\sigma = \sigma_2 = 26.16$, the effect size is 0.527 ($d = |\delta|/\,(2\sigma) = 27.57/(2 \times 26.16) = 0.527$). For two-sided *t*-test, with a level of significance of 0.05, and from the operating characteristic curves [99] attached in Appendix D, it can be determined that n^* =50. Finally, the required sample size is 26 ($n = (n^*+1)/2 = (50+1)/2 = 25.5$).

The sample size obtained from the above method assumed that standard deviations were equal. However, it can be seen that the two standard deviations were not equal in this case. If we let $\sigma = \sigma_1 = 9.80$ and repeat the procedure, it can be obtained that the required sample size is 6. The sample size calculated using the smaller standard deviation is also smaller.

If we us both standard deviations of subjective driver fatigue scores at the beginning and the end of the experiment, the calculation described by Prajapati, et al can be used [98]. The method is much more complicated and software such as GPower is needed to handle calculations. The result indicates that the minimum number of subjects is fifteen. It can be seen that the required sample size obtained from both standard deviations is between the two results obtained using only one of the two standard deviations. Recognizing that a larger number of subjects increases the chance of obtaining more statistically reliable results, a goal of recruiting 20 to 40 participating subjects was set for the first experiment.

Thirty one subjects (26 male and 5 female) participated voluntarily in this experiment. Fourteen of these subjects were from the University of New Brunswick (UNB), and seventeen were from McMaster University. Their ages range from 19 to 37 years, with mean age of 28.6 years. Each subject was required to hold a valid driver's license for at least one year. The driving experience ranges from 1 to 12 years, with mean experience of 6 years. All subjects were required to sleep well during the night prior to the day coming to the experiment. The subjects were also required to take no caffeine at least four hours before the experiment. During the experiment, the subjects were not allowed to take any caffeinated drink nor cigarette. Each subject received an information letter to understand the background of the experiment and signed the consent form after arrival. The experiment design was approved by the Research Ethics Boards of UNB and McMaster University.

4.1.2 Procedure

After arrival, the subject was provided with an information letter to understand the background of the experiment, and signed the consent form. A sample of information letter and consent form is attached as Appendix C at the end of this thesis. The subject then took a 10-minute practice simulated driving task to get familiar with the driving simulator. During this practice session, the subject performed the Lane Keeping Task, Divided Attention Task, Normal Driving Task, and completed the Driver Fatigue Questionnaire.

The subject took the 1st subjective fatigue assessment by completing the SDFS in writing immediately before starting the experiment. The subject then started the first 45-minute simulated driving session, during which the 2nd and 3rd subjective fatigue assessments were completed orally after 15 minutes and 30 minutes. The 4th subjective fatigue assessment was completed in writing right after completing the first driving session. The subject took a short break (3-5 minutes) before starting the second 45-minute driving session, during which the 5th and 6th subjective fatigue assessments were taken orally after 15 minutes and 30 minutes. Immediately after completing the second session, the 7th subjective fatigue assessment was taken in writing, followed by the other short break. Then the third 45-minute driving session was initiated. The last three subjective assessments were taken in this last driving session; the 8th and 9th assessments were completed orally after 15 and 30 minutes and the 10th was completed in writing immediately after completing the third driving session. This ended the whole experiment. In addition to the SDFS, subjective fatigue was also evaluated by the SSS. The SSS was completed by the subject four times along with the 1st, 4th, 7th, and 10th SDFS in writing. Because of its format, the SSS is difficult for the subject to quickly provide an oral answer.

Besides the subjective fatigue assessment, driving performance was recorded for the Lane Keeping Tasks (LKTs) during the three simulated driving sessions. Each LKT required the subject to maintain their position at the center of the current lane and keep a constant speed of 40 miles/hour on a straight road segment for 5 minutes. During each of three 45-minute driving sessions, the subject performed four LKTs.

The subject started each of the driving sessions from a warm-up block, which was one minute long. This warm-up block allowed the subject to accelerate to the constant speed of 40 miles/hour and stabilize vehicle control for the rest of the driving session. Immediately after the warm-up block, the 1st 5-minute LKT was started. After the 5-minute LKT, a Normal Driving Task block was followed. The 2nd 5-minte LKT was started at 15 minutes after initiating the driving session. Between the 2nd and the 3rd LKT was the second Normal Driving Task block. After completing the 3rd LKT, a short Normal Driving Task block was performed. The 4th LKT started at 40 minutes after the driving session was initiated. The driving session was ended after the 4th LKT was completed. During each of the four LKT blocks, the three groups of driving performance measures were recorded by the simulator during the LKT for later analysis. The eight parameters recorded by the driving simulator include (1) steering wheel angle input, (2) steering wheel rate, (3) yaw rate, (4) lateral position, (5) lateral velocity, (6) lateral acceleration, (7) longitudinal velocity, and (8) longitudinal acceleration, which were already described in detail in section 2.3. The sixteen driving performance parameters were calculated based on these recordings.

A psychomotor test, the Divided Attention Test (DAT), was also introduced to observe driver states during the prolonged driving task. The subject was asked to depress a button (one of the divided attention buttons as shown in Figure 3) as soon as possible when a signal was provided on the screen, which is used to display the road scenario, and the reaction times were recorded. The 1st DAT was performed right after the 1st SDFS, at the very beginning of the first driving session. The rest of the DATs were performed just before each of the SDFS during the driving sessions. Therefore, ten DATs were completed throughout the experiment; each test was close to the corresponding SDFS. Details of the DAT are provided in section 4.1.5. The time line of the experimental procedure is illustrated in Figure 1.

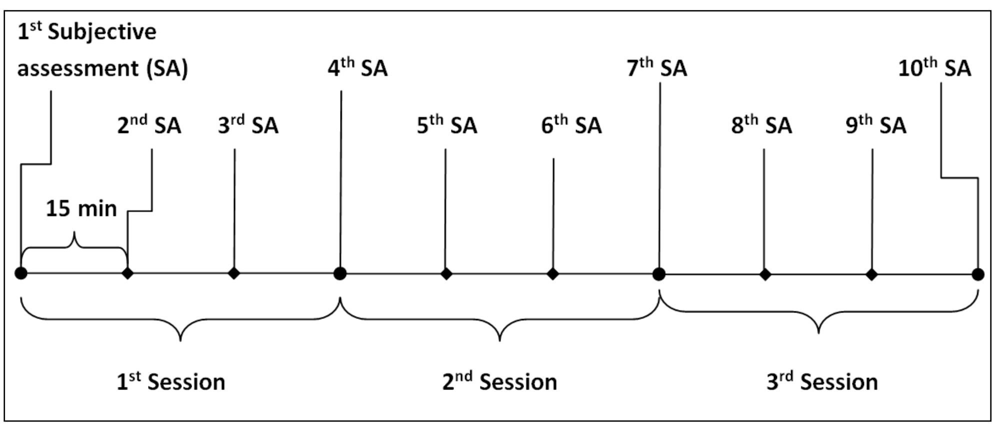


Figure 1 Time line of the experiment

4.1.3 Apparatus

The driving simulation system consists of a desktop computer, a 24-inch widescreen LCD monitor, a Logitech G27 steering wheel, and driving simulation software. The details of these components are as follows. The hardware of the simulation system includes a Dell™ OPTIPLX™ 780 desktop, a Dell™ 24-inch widescreen LCD monitor, a Logitech G27 Racing Wheel. The driving simulation system is running on a Dell™ OPTIPLX™ 780 desktop computer, with an Intel® Core™ 2 Duo CPU E8400 rated at 3.00GHz and 4 gigabyte of RAM. An NVIDIA GeForce 9300 graphics adaptor is used to obtain high quality display results. The Dell™ 24-inch widescreen LCD monitor is used to provide a visually realistic driver's view of the roadway and surrounding environment. It provides about 90 degrees of driver's front view and back view through a "rear mirror" near the right-upper corner.

Another major component of the simulation system is the Logitech™ G27 Racing wheel, which allows the driver to control the vehicle and perform various cognition tests (such as divided attention tests). Figure 2 shows an overview of the G27 Racing wheel. The major components of the controller include an 11-inch leather-wrapped rim (steering wheel), a 900^{o} force feedback wheel rotation, stainless steel gas / brake / clutch pedals, a six-speed gated shifter and a foldable seat. The dual-motor force feedback mechanism allows high-fidelity force effects, mimicking the effects of real road curvatures and surface conditions on a steering wheel. The six-speed gated shifter, as shown in Figure 3, allows the driver to choose the proper gear for the turn, with indicator LEDs telling the driver the shift position. However, to minimize distraction of the driver, the shifter was disabled, and the "vehicle" was set as automatic, instead of standard. The driver did not need the shifter during the driving sessions, therefore, completely focused on the driving task. The foldable seat allowed drivers to adjust their driving position and comfortably operate the driving simulator as in a family car.

Figure 2. Logitech G27 Racing Wheel

Figure 3. RPM/Shifter Indicator LEDs and buttons

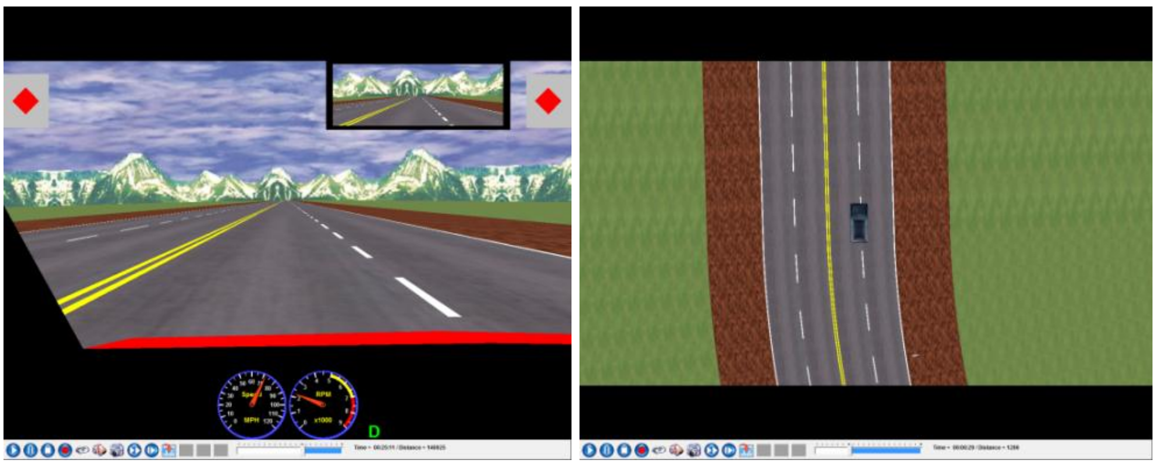
The operating system is Microsoft Windows® 7. The simulation software is STISIM Drive® V2.0, which is a product of Systems Technology, Inc. (STI). It is a PC-based driving simulator developed for vehicle dynamics and control and related human/machine interaction and human factors analysis. Customized road scenarios are designed for the three sessions. Data, including divided attention task records and driving performance records, are automatically collected by the system for later analysis.

4.1.4 Road scenario

One of the advantages of using a driving simulator is that the traffic environment can be precisely controlled and repeated; therefore, each subject can experience the same traffic conditions during the experiment. The simulation software, STISIM Drive® V2.0, provides a virtual environment and platform allowing users to design customized road scenarios. The road scenario used in this experiment appeared as a four lane highway, with lane width of 12 feet. Each driving session involved a 45-minute continuous driving task, comprising an LKT block and normal driving blocks. The LKT block contained a straight road segment with a few oncoming vehicles and no intersections. This type of road scenario ensured that drivers focused on the driving task. The normal driving block involved more complicated traffic conditions, including left and right curves and S-bends, many oncoming vehicles and obstacles (stopped vehicles, crossing pedestrians, etc.). These types of road scenarios mimic traffic conditions experienced in daily driving tasks, and increase the workload of the subjects, thus inducing driver fatigue rapidly.

The basic settings of the driving scenarios are similar to each other. Each road scenario consists of a four-lane highway road: with a double yellow line at the center of the road. In each direction there are two lanes which are divided by a white dashed line. The width of each lane is 12 feet. The color of the lane is gray, representing a regular concrete road surface. There is grass along each side of the road. Between the outer side lane and grass is a dark brown shoulder.

The background of the road scenarios was set to be mountains, which is the default setting, providing a 360 degree mountain range on the horizon and including some clouds in the sky. This background represents a sunny day, but without direct sunlight interfering with driver's visibility. The distance that the driver can see ahead of the vehicle, in this type of background, is approximate 2500 feet (762 meters). A typical view of the road scenario with background is shown in Figure 4(a). Figure 4(b) shows the overview of the vehicle travelling on this road.



(a) (b)

Figure 4. A typical view of the road scenario (a) 4-lane road highway and mountain background, (b) overview of the road scenario

Each driving session includes some vertical and horizontal curvatures. Several vertical curvatures are represented by the appearance of uphill or downhill events, randomly distributed along the journey. Horizontal curvatures represent right or left turns, with a right- or left-curve-ahead-traffic sign displayed on the right hand side of the road. The driver will initially see the curve sign when it is 300 feet from the vehicle. There are thirteen horizontal curvatures in total, approximately evenly distributed along the whole trip.

The speed limits are set as 40 miles/ hour (mph). Twelve speed limit signs are evenly distributed along the whole journey to (1) remind the driver to keep within the appropriate speed limit, and (2) allow the simulation system to determine whether the driver is driving under or over the speed limits. Each speed limit sign is displayed 500 feet in front of the driver when he/she is approaching the sign. If the vehicle travels at a speed exceeding that specified by the speed limit sign, it will be recorded and written into the data file. The total length of each scenario is 250000 feet (76.2 km). The traffic density and surrounding environment are different in each road segment to provide various complexities of traffic conditions. Two types of road scenarios are used in this experiment.

The first road scenario is monotonous and used in LKT blocks to minimize external stimulation to the subjects; therefore, driving performance recorded during these straight road segments represents the ability of the subject to control the vehicle, instead of ability to deal with emergency situations (such as avoid collision with pedestrians, etc.). This monotonous environment includes only some trees and buildings on each side of the road, which represents typical views encountered by Canadian drivers traveling between urban areas. No intersection or traffic light was included in this straight road segment, so the subject can keep a constant speed at 40 mph. There was no traffic in the same direction of the subject, but a few other vehicles were coming from the opposite direction. This low traffic rate makes the road scenario realistic, while also reducing external stimulation to the subject. This monotonous road scenario is essential to the LKT and parameters recorded to represent driving performance. Driving performance not only can be influenced by driver fatigue, but also can be affected by traffic conditions, such as surrounding vehicles, traffic lights, road surface roughness (for example, potholes on the road), visibility, etc., which the effects are difficult to identify and separate from the effects of driver fatigue. The road scenario has been designed to minimize influences from these factors.

According to previous research [41, 49], the most common form of task related fatigue is active fatigue, which is induced by mental overload tasks (or high demand driving conditions for drivers). Therefore, the second type of road scenario was more complex and used in normal driving blocks to increase driver fatigue. In one of these normal driving blocks, the driver will see some buildings along the road, with a few other vehicles coming from the opposite direction. Traffic lights at intersections may require the driver to stop; then the driver will drive on a four lane highway with trees along each side of the road. Oncoming traffic appears occasionally from the opposite direction. Several stop signs require the driver to stop at intersections. In another normal driving block, the driver travels through a city with many commercial buildings, more pedestrians, and vehicles, and more traffic lights. The driver encounters some obstacles (such as vehicle parked in the road and barrel objects), and streams of various vehicles from either the opposite direction or the driver’s own traveling direction. These complex road environment and traffic conditions not only make the road view more interesting and less monotonous, but also increase external stimulation to the driver. This requires more attention and concentration from the driver.

4.1.5 Tasks

During each driving session, two tasks are performed by the subjects. The first task is the Lane Keeping Task, during which driving performance is recorded for individual subjects for later analysis. The second is the Divided Attention Task, the reaction time of which is recorded to reflect the status of the subject.

The LKT is designed to estimate driving performance. To ensure that the changes in driving performance only resulted from variation in driver status, all the road scenarios are the same in the LKT blocks. The road scenario has been described in section 4.1.4. At the beginning of the LKT block, an audio notification is provided to the subject to initiate the LKT. During the task, the subjects are instructed to do their best to (1) keep the vehicle at the center of the lane, (2) drive as straight as possible, and (3) maintain the speed at 40 mph. Each of the LKTs lasts for five minutes, and another audio notification is given at the end of the LKT.

The second task is a psychomotor test, the Divided Attention Task. To estimate driver fatigue, DATs are performed during the driving sessions. A red diamond symbol displayed on the left or right hand side of the screen (similar to the right or left rear mirror positions) changes to a red triangle, prompting the subject to press the left or right attention button. The subject is required to respond as quickly as possible to these stimuli. Five reaction times of each set of DAT are recorded. If the subject misses any stimulus, these missing responses are also recorded. The following Figure 5 shows an example of the divided attention task. The red diamond symbol on the left hand side is replaced by a red triangle pointing to the left, while the red diamond symbol on the right hand side remains unchanged. This requires the subject to respond to the stimulus as quickly as possible by pressing the left attention button, to make the triangular symbol return to original diamond shape.

Figure 5 Divided Attention Task (DAT).

4.1.6 Variables

The independent variable is time. Dependent variables include subjective fatigue assessment, psychomotor assessment, and driving performance assessment. Each of three driving sessions is 45 minutes long; therefore, the total driving time is 135 minutes. The dependent variables are measured throughout the experiment. The overall change of a variable indicates the difference of this variable between the initial and final measurements. The inter-session change estimates the difference between the measurements at the beginning and the end of a driving session. Each dependent variable is subjected to the overall change and inter-session change analysis.

Subjective fatigue assessments. Three variables are used for the subjective fatigue assessment: the SDFS, residual driver capacity, and the SSS. The first variable, SDFS, is obtained from the Driver Fatigue Questionnaire described in Table 10 and Equation 1. The second variable, residual driver capacity is also obtained from the questionnaire.

The questionnaire is administered every 15 minutes and 10 times in total throughout the experiment. The third variable, SSS, is obtained at the beginning of the 1st driving session and the end of each driving sessions; therefore, SSS is estimated only four times for subjects who complete the whole experiment.

Psychomotor assessment. The psychomotor test, DAT, examines the reaction time of the subjects to determine their changing states. After the 1st DAT at the beginning of the experiment, DATs are taken every 15 minutes throughout the experiment; therefore, 10 sets of DATs are taken by an individual subject who completes the whole experiment. Each set of DAT records reaction time five times. The average reaction time is calculated to reflect driver states. If any test is missed, the driving simulator will also record the number of tests being missed and corresponding time.

Driving performance. Sixteen variables are used for driving performance assessment. Eight measurements listed in Table 1 are recorded by the simulating system during the LKT blocks, with a frequency of 20Hz. The mean value of each measurement is calculated to represent the averaged performance, and the standard deviation (SD) is also calculated to represent the performance variance. Thus, sixteen variables are obtained to determine driving performance. Detailed calculation of these variables is given in section 5.13 to reflect the ability of the subject in steering wheel control, lateral position control, and speed control.

4.2 The 2nd Experiment

The second experiment investigates the effectiveness of the two fatigue countermeasures, consuming caffeine and listening to music. These two methods have been reported to be two of the most frequently adopted and most effective [88]. However, to date, there has been no study investigating the effects of and difference between these two. The two countermeasures are to be compared in this experiment. Each individual subject completed three 120-minute driving sessions: control, caffeine, and music sessions on three different days. The effects on subjective fatigue, residual driver capacity, and driving performance are quantitatively observed. The brain activity of the subject is also investigated as an additional fatigue assessment. Details of the experiment setup are included in this section.

4.2.1 Subjects

Based on the data obtained from the 1st experiment, a minimum of 13 subjects are required, determined by the power analysis software Gpower [98] and following the procedure described in section 4.1.1. To ensure adequate statistical reliability and significance, a goal of recruiting 15 to 25 participating subjects was set for the second experiment.

Twenty healthy students (10 male and 10 female) from McMaster University participated in this experiment. Their ages range from 18 to 34 years, with mean age of 22.5 years. As required in the first experiment, each subject is asked to hold a valid driver's license for at least one year. The driving experience ranges from 1 to 7 years, with mean experience of 3.1 years. Regardless being regular coffee drinkers or being non-regular coffee drinkers, all twenty subjects have no allergy to caffeinated drink. Again, each subject is required to sleep well during the night prior to each of three days coming to the driving simulation laboratory. The subjects are also required to take no caffeine at least four hours before each driving session. During the driving sessions, the subjects are not allowed to take any caffeinated drink nor cigarette. Each subject received an information letter to understand the background of the experiment and signed the consent form after the first time arrival. Every subject received $50 CAD compensation after completing the experiment. The experiment design was approved by the McMaster University Research Ethics Board.

4.2.2 Procedure

The second experiment consists of three 120-minute driving sessions: control, caffeine, and music sessions. Each subject needs to complete the three sessions on three different days. To minimize circadian rhythms in fatigue, the subject is asked to start each of the three driving sessions at the same time of each day. During the control session, subjects operate the steering wheel and gas/braking pedals to control the vehicle, presented with a carefully designed road scenario. The caffeine session is identical to the control session, except that each subject takes 405 ml Starbucks® Bottled Mocha Frappuccino® right before the driving session. This provides 108 mg caffeine to each subject. With the average weight being 66.7/kg for the twenty subjects, it means 161.9 mg/100kg intake of caffeine on average. The music session is also identical to the control session, except the driver can listen to the music throughout the driving session. The subject is allowed to choose his/her favorite music/songs for the music session. Electrodes are attached to collect EEG signal before starting each driving session.

Control session. The control session is very similar to the 1st experiment, except that (1) the overall driving time is 120 minutes instead of 135 minutes, and (2) the subject operates the driving simulator continuously throughout the whole session without any break. The subject took the 1st subjective fatigue assessment by completing the DFQ in writing right before the driving session. During the control session, the DFQ is administered orally every 15 minutes until the end of the control session. After completing the control session, the last DFQ is administered in writing again. Therefore, the DFQ is administered 9 times in total, two in writing right prior and after the control session and seven orally during the control session. Similar to the 1st experiment, driving performance is recorded during the LKT blocks. The subject performs nine LKTs every 15 minutes and eight parameters are recorded as in the 1st experiment. Each LKT block is followed by a 10-minute normal driving block. During each LKT, the EEG signal is also recorded with a sampling frequency of 480 Hz for later analysis.

Caffeine session. The caffeine session is identical to the control session, except that the subject is asked to take a bottle of 405 ml Starbucks® Bottled Mocha Frappuccino® prior to the driving task. The caffeinated drink provides 108 mg caffeine to each subject. The average weight of the subjects is 66.68kg; therefore, it means 161.9 g/100kg intake of caffeine in average. Then the subject completes the driving session as in the control session. The SDFS and driving performance and EEG are recorded as in the control session as well.

Music session. The music session is also identical to the control session, except that subjects are asked to play their favorite music throughout the driving session. The subject brings a music playing device (such as MP3 players or a smartphones), which is connected to a speaker. The subject adjusts the volume to a comfortable level, and then starts the driving task. During the driving session, the subject can adjust the volume or change the music at any time, just like operating an in-vehicle music device. While performing the driving task and listening to the music, the SDFS and driving performance and EEG are recorded as in the control session.

4.2.3 Apparatus

The same driving simulation system described in the 1st experiment is also used in this experiment, except the 24-inch widescreen LCD monitor is replaced by a 40-inch widescreen LCD monitor. This 40-inch screen makes the road scenario much more realistic. The other hardware and software remain unchanged. In addition to the driving simulation system, wireless EEG equipment, CleveMed (as shown in Figure 6), is used to collect EEG signal of the subject during driving sessions.

During each session, two channels of EEG are recorded, both from the frontal regions, as shown in Figure 7. Four gold cup electrodes are used in the experiment. Two gold cup electrodes are placed at locations FP1 and FP2 to collect EEG signal, one gold cup electrode is placed at middle of the forehead (FpZ) for ground, and one gold cup electrode is placed on the right mastoid process (A1) as reference.

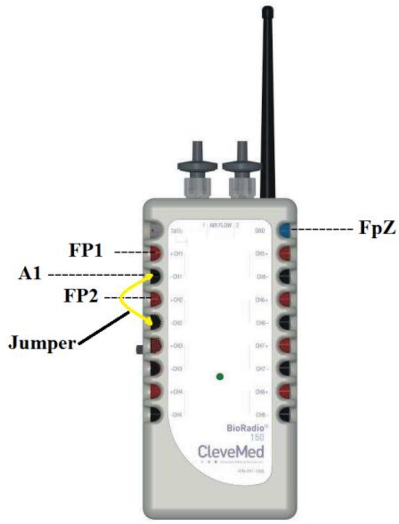


Figure 6 CleveMed wireless EEG equipment

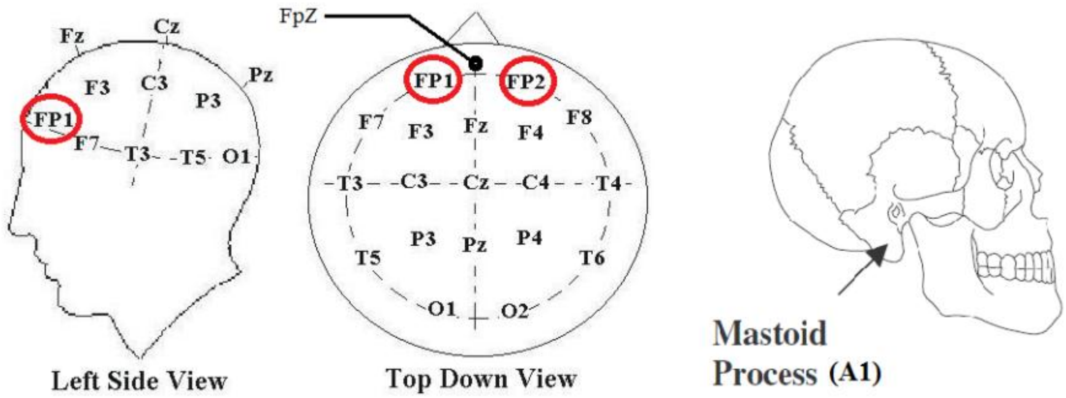


Figure 7.Two channels of EEG were recorded from the Frontal region, highlighted as FP1 and FP2,

The gold cup electrode is first filled with conductive gel and attached at position FP1. A Life Brand® round sport bandage was applied over the gold cup electrode to secure it on the position. This procedure is repeated for the other gold cup electrodes at locations of

FP2, FpZ, and A1. The electrode placements are illustrated in Figure 7. The sampling frequency is 480Hz, which is the default setting of the equipment.

4.2.4 Road scenario

The road scenarios in the 1st experiment are used in the 2nd experiment. The monotonous LKT block and the complex normal driving block are used alternatively throughout the driving session. Each LKT block is 5 minutes and each normal driving block is 10 minutes. Details of the road scenarios are included in section 4.1.4.

4.2.5 Tasks

LKTs are performed in each driving session, as subjects performed in the 1st experiment. Details are provided in section 4.1.5.

4.2.6 Variables

The independent variables are time and driving sessions. Dependent variables include subjective fatigue assessment, driving performance assessment, and EEG assessment. Each of the three driving sessions is 120 minutes long. The other independent variable is driving session: control, caffeine, and music sessions. The difference/changes of dependent variables against time and three driving sessions are to be examined. The dependent variables are measured throughout the experiment. The overall change of a variable indicates the difference of this variable between the initial and final measurements of a driving session. The inter-session change estimates the difference among the measurements of the three driving sessions (at the same time point).

Each dependent variable is subjected to the overall change and inter-session change analysis.

Subjective fatigue assessments. Two variables are used for the subjective fatigue assessment: the SDFS and residual driver capacity. The two variables are measured in the same way as in the 1^{st} experiment, using the questionnaire listed in Table 10.

Driving performance. Sixteen variables used in the 1^{st} experiment are also measured and calculated in the same way in this experiment.

EEG assessment. Each subject performs three driving sessions (control, caffeine, and music sessions). In each driving session, the EEG signal is collected, and the data during the nine 5-minute LKT blocks are analyzed to examine brain activities of the subject, corresponding to the time periods when the SDFS is calculated. Therefore, 9 sets of EEG data are collected during each driving session, and 27 sets are collected for the whole experiment for an individual subject who completed the whole experiment. Each set of EEG data includes recordings at FP1 and FP2, which are denoted as $fp_1(t)$ and $fp_2(t)$. Therefore, the EEG signal of the m^{th} subject recorded at the FP1 and FP2 positions during the T^{th} LKT in the one of three driving sessions are denoted as ${}_{T}^{s}fp_1{}^{m}(t)$ and ${}_{T}^{s}fp_2{}^{m}(t)$ respectively; where m ranges from 1 to 20, T ranges from 1 to 9, and s ranges from 1 to 3 (1 = control session, 2 = caffeine session, and 3 = music session). The unit is μv. For example, the EEG signal of the 8^{th} subject recorded at FP1 during the 4^{th} LKT block in the caffeine session is denoted as ${}_{4}^{2}fp_1{}^{8}(t)$, and the raw data recorded at FP2 is denoted as ${}_{4}^{2}fp_2{}^{8}(t)$. Averages of ${}_{T}^{s}fp_1{}^{m}(t)$ and ${}_{T}^{s}fp_2{}^{m}(t)$ are calculated and denoted as ${}_{T}^{s}fp^{m}(t)$, which is mathematically represented by Equation 2. Data analysis on the averaged EEG is presented in the following section.

$$ {}_{T}^{s}fp^{m}(t) = \frac{{}_{T}^{s}fp_1{}^{m}(t) + {}_{T}^{s}fp_2{}^{m}(t)}{2} $$ Equation 2

The wave described by ${}_{T}^{s}fp^{m}(t)$ was decomposed into four frequency components of EEG and noises. The four frequency components can be obtained from the recordings which are delta (δ, 0.5~4 Hz), theta (θ, 4~8 Hz), alpha (α, 8~13 Hz), and beta (β, 13~20 Hz) waves. The four components are denoted as ${}_{1}^{1}\delta^{1}(t)$, ${}_{1}^{1}\theta^{1}(t)$, ${}_{1}^{1}\alpha^{1}(t)$, and ${}_{1}^{1}\beta^{1}(t)$ respectively, again, $t = 0 \sim 300$ seconds. Based on the EEG signal, eight variables can be calculated to investigate the subject states. These variables are (1) power spectra of the four components and (2) four ratios of slow wave to fast wave that have been suggested as fatigue indicators by Jap et a.[77]. The details of these eight variables are given in Chapter 6.

At the end of this chapter, an overview of the setup of the 2nd experiment is provided in Figure 8. The road scenario is displayed on the 40-inch widescreen, at a comfortable distance between 0.8~ 1.3 meters in front of the subject. The subject is seated in the Playseat, which is adjustable and allows the subject to change positions of the steering wheel and the seat. The EEG signal collecting part of the CleveMed wireless EEG equipment is mounted at the back of the Playseat.

Figure 8. Overview of the setup of the 2nd experiment, with 40-inch widescreen monitor and wireless EEG equipment

Chapter 5 The First Experiment (*Data Analysis*)

The data analysis of the first experiment will be represented in this chapter, including changes in the SDFS, residual driver capacity, SSS, and various driving performance parameters. The independent variable was driving time (and driving sections completed). A series of paired student *t*-tests were performed to check whether changes in each parameter were significant after completing all three driving sessions. Then one-way ANOVAs were used to examine whether changes in each parameter were significant with time. Multi-comparisons were performed using the Tukey test [100]. All analyses were conducted at the 0.05 significance level, unless otherwise noted. The results are presented in the following sections. A part of the results in the first experiment was published in [101].

5.1 Overall Changes

It is of interest whether the value of each parameter at the end of the experiment is significantly different from the initial value, which is the overall change. It is expected that after three driving sessions, the subject is more fatigued than at the beginning of the experiment. If the subjective driver fatigue assessment tool is a valid driver fatigue indicator, then the SDFS should increase significantly and residual driver fatigue should decline significantly after the experiment. Meanwhile, driver performance is expected to change significantly. Therefore the parameters reflecting driving performance will be examined to check the overall changes.

5.1.1 Items of DFQ

To validate DFQ, the overall change in each item should be examined. For each item, the scores of the thirty-one subjects at the beginning and end of the experiment are compared using paired student *t*-tests. For example, the 8th item asks whether the subject's feet are sore at that moment. The individual score ranges from 1 to 10, with 1 being not sore at all and 10 being extremely sore. The average score is 1.71 for the thirty-one subjects at the beginning of the experiment, meaning the subjects experience low soreness on their feet. After finishing three driving sessions, the average score increases to 5.35, meaning the group, on average, experiences slightly more than moderately sore a feet. The overall change in the average score of the 8th item is 3.64. The results of paired student *t*-test showed that the overall change in the score of the 8th item is significant [p= 9.916E-10, t=-8.45, CI = (-∞, -2.9129)]. This result is included in part A of Table 11, along with the results of the remaining eleven items. It can be seen that all the items, except the 6th item, have shown significant changes after the experiment. The 6th item asks whether the subject will pass a leading vehicle which is much slower than the driver, assuming that the driver is currently on the highway. The result of the student *t*-test has shown that *p* value is 0.072, which is greater than 0.05. Although the result suggests the overall change in the score of the 6th item is not significant, the score shows a trend of an increase for the whole group. Recall that for the 12th item, the score (or answer) of residual driver capacity, has a different scale. The numerical answer provided by the subject is the number of hours that he/she can safely control the vehicle; therefore, it has a unit of hour and can be any reasonable positive number. The result shows that the average driver capacity is 3.9 hours at the beginning of the experiment, and reduced to 1.05 hours after the experiment. Driver capacity has reduced 2.85 hours in average, after 2 hours of simulated driving. This may suggest that the experiment setup can induce driver fatigue more rapidly than normal daily real on-road driving. This result agrees with the expectation of the road scenario design.

Table 11 Change in Subjective assessment before and after simulated driving

	Initial Score	Final Score	Difference	t-test (p)	ci	standard deviation	t-statistic
A. Individual Scores							
Q1	3.4516	5.8710	2.4194	0.00	(-∞, -1.437)	3.223	-4.18
Q2	3.9032	5.7742	1.8710	0.00	(-∞, -0.914)	3.138	-3.32
Q3	3.4194	5.4516	2.0323	0.00	(-∞, -1.0445)	3.2402	-3.49
Q4	1.4516	2.3871	0.9355	0.01	(-∞, -0.2726)	2.1746	-2.40
Q5	2.7097	5.2258	2.5161	0.00	(-∞, -1.6616)	2.8032	-5.00
Q6	2.9677	3.7742	0.8065	0.07	(-∞, 0.1061)	2.9935	-1.50
Q7	2.9032	5.7419	2.8387	0.00	(-∞, -1.7854)	3.4554	-4.57
Q8	1.7097	5.3548	3.6452	0.00	(-∞, -2.9129)	2.4021	-8.45
Q9	1.9355	4.0000	2.0645	0.00	(-∞, -1.1848)	2.886	-3.98
Q10	1.7419	4.5806	2.8387	0.00	(-∞, -1.9762)	2.8296	-5.59
Q11	1.4839	5.1290	3.6452	0.00	(-∞, -2.8442)	2.2674	-7.72
Q12	3.90	1.05	-2.85	0.00	(2.3259, ∞)	1.7192	-9.23
B. SSS and SDFS							
SDFS	27.6774	53.2903	25.6129	0.00	(-∞, -18.51)	23.30	-6.12
SSS	2.3871	4.1290	1.7419	0.00	(-∞, -1.33)	1.366	-7.10

It can be concluded that individual items in the questionnaire are valid to estimate subjective fatigue for the driver, since the overall changes in the scores of each item are significant, except the 6th item. Although the change in score of the 6th item is not significant, a clear trend of increase can be observed. This suggests that it also reflects driver states and can be included in the DFQ for subjective driver fatigue assessment.

5.1.2 SDFS and SSS

The SDFS can be calculated using Equation 1, and the SSS is obtained directly from the answer-sheet of the questionnaire. It is expected that both SDFS and SSS are increased after completing the prolonged driving task. The overall changes are examined using student *t*-tests. The result shows that the average SDFS of the thirty-one subjects was 27.7 at the beginning of the experiment. After the experiment, the SDFS increases by 25.6 to 53.3, as expected. The student *t*-test shows that the overall change in the SDFS is significant [p= 4.98E-07, t = -6.12, CI = (-∞, -18.51)].

The average sleepiness estimated by the SSS is 2.387, suggesting the subjects on average are functioning at high levels but are a little bit relaxed. After the prolonged driving task, the SSS increases by 1.742 to 4.129, suggesting the subjects are somewhat tired but still awake. The student *t*-test shows the overall change in the SSS is significant [p= 3.36E-07, t =-7.10, CI = (-∞, -1.33)]. This is as expected and reasonable, because the mental component of driver fatigue may lead a subject into sleep [8, 12]. However, driver fatigue is distinct from sleepiness; therefore, the increase in SDFS should be different from the increase in SSS. After calculating the percentage of increase, it shows that the SDFS increases 26% and SSS increases 29%. It seems the SSS increases slightly more rapidly than the SDFS.

The result may suggest that the driver fatigue indicator, the SDFS, is closely related to the sleepiness index, the SSS, but the SDFS is not identical to the SSS. Because the sleepiness is the only one of many symptoms of driver fatigue being assessed, and the SDFS includes all these factors.

5.1.3 Driving performance

The variables listed in Table 1 are used to estimate driving performance. The first group includes the means and standard deviations of steering wheel angle input (SA) and steering wheel rate (SR) and yaw rate (YR), representing driver ability to control the steering wheel. The simulator system has an accuracy of 0.01^{o} for the SA, 0.001 rad/s for the SR, and 0.001 rad/s for the YR.

The second group includes the means and standard deviations of lateral position (LP) and velocity (LV) and acceleration (LA), measuring the driver ability to control lateral position. The simulator system has an accuracy of 0.01 ft for the LP, 0.01 ft/s for LV, and 0.01 ft/s^{2} for LA.

The third group includes the means and standard deviations of longitudinal speed (VE) and acceleration (AC). The simulator system has an accuracy of 0.01 ft/s for the VE, and 0.01 ft/s^{2} for the AC. In this section, each variable is examined to determine whether the overall change is significant after completing the 135 minute simulated driving task.

Steering wheel control. The variables in the first group include the means and standard deviations of SA, SR, and YR, reflecting driver abilities to control the direction of the vehicle by handling the steering wheel. To illustrate how the analysis proceeded, details of analysis on SA are described as follows.

The steering wheel angle, SA, is recorded at a frequency of 20Hz during each of the 5-minute LKTs. The SA for the *m*th subject is denoted as ${}_{t}sa_{n}^{m}$, where $t = 0,15,\ldots,120,135$, which is driving time; $m = 1 \sim 31$, which is the identity of the subject; $n = 1 \sim 6000$, which is the index of SA being recorded during the LKS started at t. The mean SA of the *m*th subject started at t, denoted as $\overline{{}_{t}\,sa^{m}}$, is calculated using Equation 3. The related standard deviation of the steering wheel angle input, denoted as ${}_{t}\sigma_{sa}^{m}$, is calculated using Equation 4. The group average of the mean SA at time *t* is then calculated for all thirty-one subjects using Equation 5, and denoted as $\overline{{}_{t}SA}$. The group average of standard deviation of the SA is calculated using Equation 6, and denoted as $\overline{{}_{t}\sigma_{sa}}$.

$$\overline{{}_{t}sa^{m}} = \left(\sum_{n=1}^{6000} {}_{t}sa_{n}^{m}\right)/6000 \quad \text{Equation 3}$$

$${}_{t}\sigma_{sa}^{m} = \sqrt{\sum_{n=1}^{6000}\left({}_{t}sa_{n}^{m} - \overline{sa^{m}}\right)^{2}/6000} \quad \text{Equation 4}$$

$$\overline{{}_{t}SA} = \sum_{m=1}^{31}\left(\overline{{}_{t}sa^{m}}\right)/31 \quad \text{Equation 5}$$

$$\overline{{}_{t}\sigma_{sa}} = \sum_{m=1}^{31}\left({}_{t}\sigma_{sa}^{m}\right)/31 \quad \text{Equation 6}$$

where

${}_{t}sa_{n}^{m}$ = the *n*th steering wheel angel input (SA) during the LKT started at *t* for *m*th subject

$\overline{{}_{t}sa^{m}}$ = mean of SA during the LKT started at *t* for *m*th subject

${}_{t}\sigma_{sa}^{m}$ = the standard deviation of SA during the LKT started at *t* for *m*th subject

$\overline{{}_tSA}$ = the group average of mean SA during the LKT started at *t*

$\overline{{}_t\sigma_{sa}}$ = the group average of the standard deviation of SA during the LKT started at *t*

For each subject, the initial mean and standard deviations of SA, $\overline{{}_0sa^m}$ and ${}_0\sigma_{sa}^m$, are calculated, and the final mean and SD, $\overline{{}_{135}sa^m}$ and ${}_{135}\sigma_{sa}^m$, are calculated. The overall changes are examined using student *t*-tests. The result shows that the average mean of SA for the thirty-one subjects is -0.0007^o at the beginning of the experiment. After the experiment, the mean of SA is calculated to be 0.0063^o, suggesting an increase of 0.007^o. It can be seen that both values are very close to zero. Subjects keep the steering wheel at the neutral position while they try to drive straight, and keep turning the steering wheel back and forth. When summation is made, positive and negative records are canceled out, resulting the mean of SA approaching zero. It is expected the overall change in means of SA is not significant. The student *t*-test confirmed this expectation [p= 0.1149, *t* = -1.23, CI = (-∞, -0.0027)]. On the other hand, the standard deviation represents the variation in SA. The result shows that the group average of standard deviation of SA is 0.6279^o at the beginning of the experiment, and 0.8237^o at the end of the experiment. There is an increase of 0.1595 ^{o} in variation of SA after 120-minute simulated driving task.

It should be noticed that the accuracy of the SA measured by the system is 0.01 ^{o}, but the calculated mean and SD presented here include four decimal places, to avoid only showing zeros in the results. The digits beyond the accuracy of the system measurement only present mathematical analysis for the data collected. For each driving performance parameters, there is no actual physical meaning for the digit beyond the accuracy listed at the beginning of this section. For example, the average group mean of SA is -0.0007^{o} at the beginning of the first session. This does not mean that an individual subject can move the steering wheel by 0.0007^{o}. It only means the average input value of the steering wheel of the group is close to zero, but not equal to zero.

The student *t*-test shows that the overall change in standard deviation is significant for SA [p= 0.007, t = -2.60, CI = (-∞, -0.0678)]. This significant increase in standard deviation of SA suggests that larger variations in angular input have occurred at the end of the experiment, indicating impaired ability to maintain the steering wheel at a neutral position. The results of the student *t*-tests are included in Table 12, along with the results of the other driving performance parameters.

Similarly, the means and standard deviations of other driving performance parameters can be calculated and analyzed in the same way shown above. The other four variables in the first group are means and standard deviations of SR and YR.

The overall change in the group mean is not significant for SR [p= 0.1094, t = -1.28, CI = (-∞, 0.0007)], nor for YR [p= 0.2336, CI = (-∞, -0.00003)]. The overall change in the group average of standard deviation is not significant for SR [p= 0.0818, t = -1.43, CI = (-∞, 0.0036)], but significant for YR [p= 0.0002, t = -3.98, CI = (-∞, -0.0009)]. These results are listed in Table 12. Therefore, none of the three group means (the means of SA, SR and YR) shows significant change after the 120-minute simulated driving task. On the other hand, two of the three group averages of standard deviations (standard deviations of SA and YR) have shown significant increases after completing the experiment.

In conclusion, the group averages of the means in direction control parameters have shown no significant changes after 120-minute simulated driving task; and two of the group averages of the standard deviations in direction control parameters have shown significant changes. This result suggests that (1) the subjects are able to maintain the vehicle travel direction on a straight pass throughout the experiment, and (2) the amplitude of steering wheel movements increases significantly after the 120-minute simulated driving task, resulting in an increase in the variation of heading angles of the vehicle at near the end of the experiment. The ability to control the steering wheel has been influenced by the prolonged driving task.

Lateral position control. The variables in the second group include the means and standard deviations of LP, LV, and LA, reflecting driver abilities to maintain the vehicle at the center of the lane. The overall change in the group mean is not significant for LP [p= 0.7938, t = 0.83, CI = (-∞, 0.5059)], is significant for LV [p= 0.0313, t = 1.93, CI = (0.00045, ∞)], and is not significant for LA [p= 0.1555, t = -1.03, CI = (-∞, 0.0014)]. The overall change in the group averages of standard deviation is not significant for LP [p= 0.5322, t = 0.08,CI = (-∞, 0.2621)], is significant for LV [p= 0.0015, t = -3.23, CI = (-∞, -0.0346)], and is significant for LA [p= 1.99E-6, t = -5.62, CI = (-∞, -0.0944)]. The results are listed in Table 12. Therefore, only one of three group means (the mean of LV) shows significant change after the 135-minute simulated driving task, and two of the three group averages of standard deviations (standard deviations of LV and LA) have shown significant increase after completing the experiment.

In conclusion, the group averages of the mean and standard deviation of LP show no significant changes after the 135-minute simulated driving task, indicating the subject consistently keeps the vehicle at the center of the lane throughout the experiment. The group averages of the mean and standard deviation of LV have shown significant increases after the prolonged driving task. For LA, the group mean shows no significant change but the group average of standard deviation shows significant increases. This result suggests that driving behaviors of the subjects have been influenced after the prolonged driving task, although the subjects still can maintain the vehicle at the center of the lane.

Longitudinal speed control. The variables in the third group include the means and standard deviations of VE and AC, reflecting driver abilities to maintain the vehicle at a constant speed of 40 mph. The overall change in the group mean is significant for VE [p= 5.0E-8, t = -6.99, CI = (-∞, -7.2051)], but not significant for AC [p= 0.0501, t = 1.70, CI = (-0.45E-5, ∞)]. The overall change in the group average of standard deviation is significant for VE [p= 2.32E-5, t = -4.76, CI = (-∞, -1.2425)], but not significant for AC [p= 0.1628, t = -1.00, CI = (-∞, 0.056)]. The results are also listed in Table 12. Therefore, both group average of the mean and standard deviation of VE have shown significant changes after 135-minute simulated driving task, but the two variables related to AC have not shown significant change.

In conclusion, the group mean of VE increases significantly, but the group mean of AC shows no significant change. Meanwhile, the group average of standard deviation is also significant for VE, but not significant for AC after the prolonged driving task.

This observation suggests that the subjects tend to speed up and are less stable in maintaining constant speed when approaching the end of the experiment.

Table 12 Overall Change in Driving Performance

	Initial value	Final value	Difference	t-test (p)	ci	sd	t-statistic
A. mean							
SA	0.00	0.01	0.01	0.1149	(-∞, 0.0027)	0.03	-1.23
SR	0.012	0.002	0.002	0.1049	(-∞, 0.0007)	0.009	-1.28
YR	0.000	0.000	0.000	0.2336	(-∞, 0.00003)	0.000	-0.74
LP	6.28	6.12	-0.16	0.7938	(-∞, 0.5059)	1.11	0.83
LV	0.001	-0.002	0.003	0.0313	(0.00045, ∞)	0.010	1.93
LA	-0.0002	0.0019	0.0021	0.1555	(-∞, 0.0014)	0.0117	-1.03
VE	59.29	68.80	9.51	5.00E-8	(-∞, -7.2051)	7.57	-6.99
AC	0.00	-0.01	-0.01	0.0501	(-0.45e-5, ∞)	0.05	1.70
B. SD							
SA	0.63	0.82	0.19	0.007	(-∞, -0.068)	0.42	-2.60
SR	0.032	0.051	0.019	0.0818	(-∞, 0.0036)	0.074	-1.43
YR	0.004	0.005	0.001	0.0002	(-∞, -0.0009)	0.002	-3.98
LP	0.95	0.93	-0.02	0.5322	(-∞, 0.2621)	0.82	0.08
LV	0.279	0.352	0.073	0.0015	(-∞, -0.0346)	0.126	-3.23
LA	0.22	0.36	0.13	1.99E-6	(-∞,-0.0944)	0.13	-5.62
VE	1.91	3.84	1.93	2.32E-5	(-∞, -1.2425)	2.26	-4.76
AC	0.22	0.30	0.08	0.1628	(-∞, 0.056)	0.45	-1.00

In summary, the overall changes in means of the variables have shown significant changes for only two variables (group means of LV and VE), and no significance for six variables (group means of SA, SR, YR, LP, LA, and AC); the overall changes in group averages of standard deviations have shown significance for five variables (SA, YR, LV, LA, and VE), and no significance for three variables (SR, LP, and AC). The subjects have shown higher levels of fatigue at the end of the experiment, as stated in section 5.1.2. As a result, variables related to driver performance have been influenced by the increased fatigue, which is induced by the 135-minute simulated driving task. Although 6 out of 8 group means have not shown significant changes, 5 out of 8 standard deviations have shown significant changes. This may suggest that, compared to mean values, standard deviations are more sensitive to driving performance deterioration due to increased driver fatigue.

5.2 Inter-sessional changes

It is of interest whether subjective fatigue levels and driving performance change significantly after completing each 45-minute simulated driving session. Variables being examined include the SDFS, the SSS, driver capacity, and various driving performance parameters. Records at the beginning of the experiment and at the end of each driving session are compared, using one-way ANOVAs; then Multi-comparisons are performed using the Tukey test [100].

5.2.1 Subjective Assessment

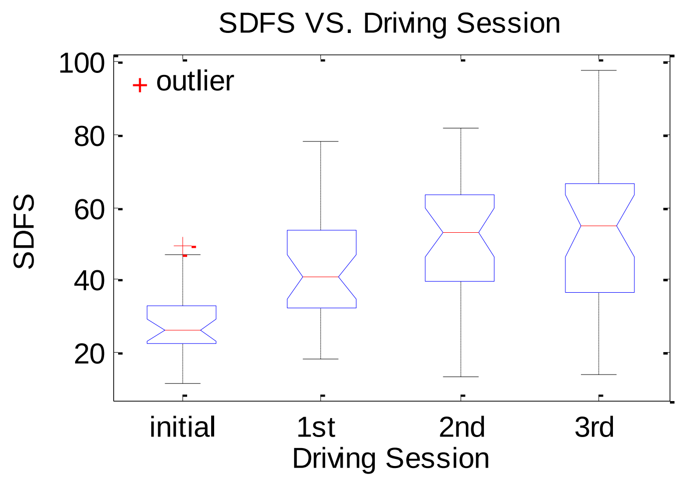
In this section, inter-sessional changes in the SDFS, residual driver capacity, and the SSS are examined.

SDFS. To investigate inter-session effects on driver fatigue, a one-way ANOVA is used to examine SDFSs before starting the experiment and those at the end of each session. Significant inter-sessional variation is observed for the SDFS [$F(3,123)=14.24$, $p=5.3E-8$]. There is very strong evidence suggesting that changes in the SDFS after a 45-minute driving session are quite significant. Multi-comparison is performed using the Tukey test. The result showed that the initial SDFS is significantly lower than the SDFS obtained at the end of each driving session. Although, no significant difference has been identified among the scores after each driving session, a clear trend of increase in the

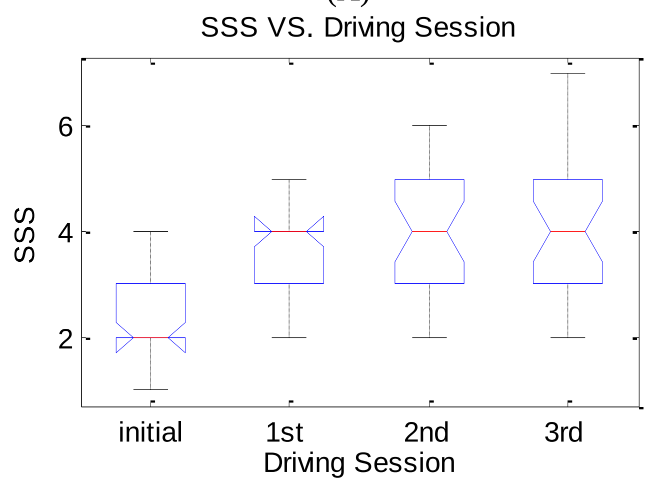
SDFS was observed, as shown in Figure 9 (A). The plot showed an outlier, suggesting that this subject started the experiment at a much higher fatigue level (SDFS = 49) than the other subjects (the group average, SDFS = 26.7). However, after finishing the three driving sessions, the SDFS of this subject was 56, which was only slightly higher than the group average (SDFS =53.3).

SSS. Analysis on the SSS shows similar results, suggesting inter-sessional changes in the SSS are significant [F(3,123)=16.83, p=3.45E-9]. Multi-comparison was also performed and showed that only the initial score is significantly lower than the scores after completing each driving session. The result is plotted in Figure 9 (B). From the plot, it can be seen that there is very little variation in the average the SSS after the 1^{st} driving session.

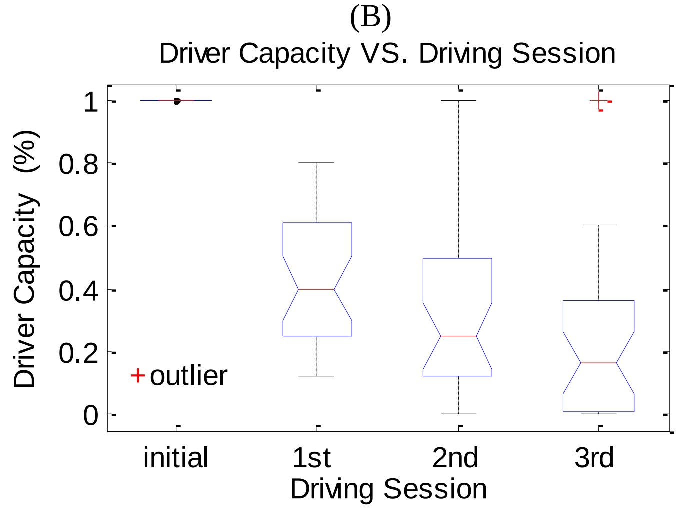
Residual driver capacity. To reduce effects of individual differences in residual driver capacities, the normalized residual driver capacity is used. The normalizing factor is the maximum driver capacity being reported throughout the experiment. To obtain normalized residual driver capacity, each score is divided by the normalizing factor of the individual subject. Therefore, the normalized driver capacities range from 1 to 0 (It can also be called the percentage of residual driver capacity). While the SDFS and the SSS increases with the number of driving sessions completed, normalized driver capacity residua is decreased significantly [F(3,123)=94.7, p=0.17E-30]. Multi-comparison has shown that initial capacity is significantly higher than the residua examined after each driving session.



(A)



(B)



(C)

Figure 9 Inter-session variations in subjective fatigue assessment: (A) SDFS, (B) SSS (C) normalized residual driver capacity

The residua after the 1st driving session are not significantly higher than the 2nd driving session, but significantly higher than the residua at the end of the 3rd driving session. The residua do not decrease significantly after the 3rd driving session. In summary, residual driver capacity decreases significantly after the 1st 45-minute driving session, and then decreases significantly after two 45-minute driving sessions. The result is plotted in Figure 9 (C).

5.2.2 Driving performance

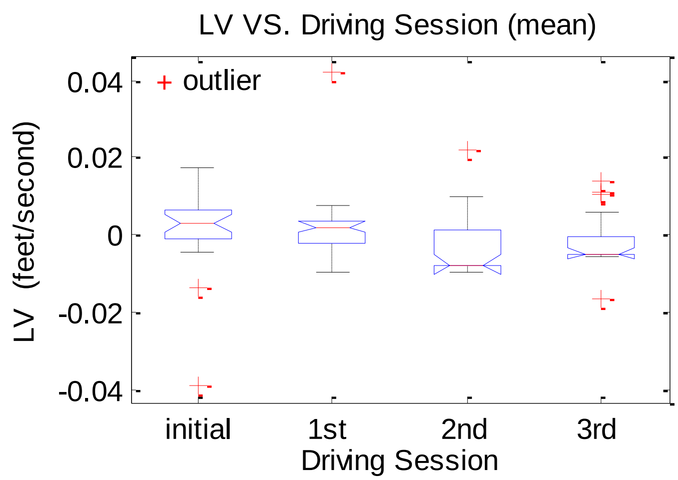
Variations in driving performance across driving sessions are examined similarly. For example, the means and standard deviations of SA at the beginning of the experiment and at the ends of each 45-minute driving session are examined using one-way ANOVAs. The result shows that inter-sessional variation in means of SA is not significant [$F(3,123) = 0.63$, $p = 0.5855$]. Multi-comparison is performed, and no significant variation in means of SA has been found between any two of the driving sessions. This is not surprising, because the overall change in means of SA has been found not significant. On the other hand, inter-sessional variation in standard deviations of SA is not significant [$F(3,123) = 1.18$, $p = 0.322$], although the overall change has been examined to be significant. The results of analysis on inter-sessional variation of all sixteen variables are listed in Table 13. Only three variables have shown significant inter-session variation: the means of LV, and the means and standard deviations of VE.

Multi-comparison shows that (1) the means of LV have significantly changed after completing the first driving session. (2) Initial means of VE are significantly different after completing two driving session and three driving session; means of VE at the end of 1st driving session are significantly different from those at the end of 2nd and 3rd driving sessions. (3) Initial standard deviations of VE are significantly different from those at the end of 3rd driving session, standard deviations at the ends of the 1st session are significantly different from those of the 2nd session, and standard deviations after 2nd session are significantly different from those of the 1st and 3rd sessions. The plots of these three variables showing significant inter-sessional variation are also shown in Figure 10.

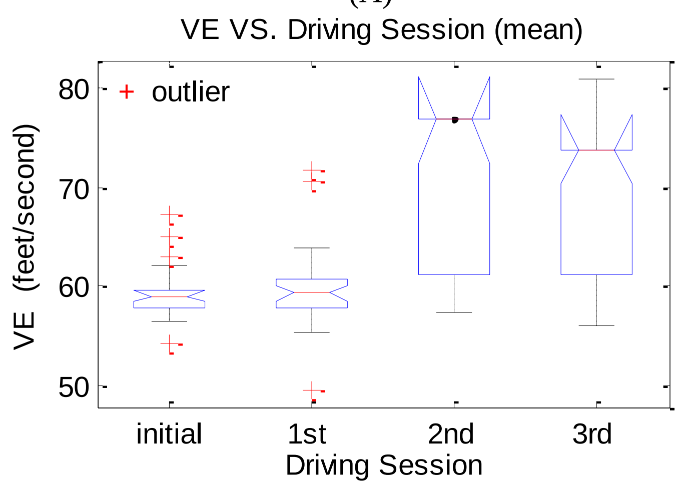
Table 13 Inter-sessional Variation in Driving Performance

	mean			SD		
	F(3,123)	p	Tukey test	F(3,123)	p	Tukey test
SA	0.65	0.5855	none	1.18	0.322	none
SR	1.48	0.2237	none	0.64	0.5882	none
YR	0.94	0.4269	none	1.43	0.2377	none
LP	0.52	0.6705	none	0.17	0.9133	none
LV	3.41	0.0197	1-2	2.44	0.0676	none
LA	1.02	0.3847	none	2.05	0.1099	none
VE	30.24	1.243E-14	0-2,3; 1-2,3	9.49	1.125E-5	0-3; 1-2; 2-1,3
AC	2.11	0.1031	none	1.69	0.172	none

The results showed that driver fatigue accumulated rapidly first, and then showed a trend of gradual increase throughout the rest of the experiment. Increases in driver fatigue had negative impact on driving performance. The negative impact was indicated by changes in driving performance parameters (such as means of LV, means of VE, and standard deviations of VE). Since less driver fatigue was accumulated in a 45-minute driving session, less impact of driver fatigue on driving performance was expected. Therefore, it is reasonable to see less significant changes in driving performance parameters, as shown in Table 13.



(A)



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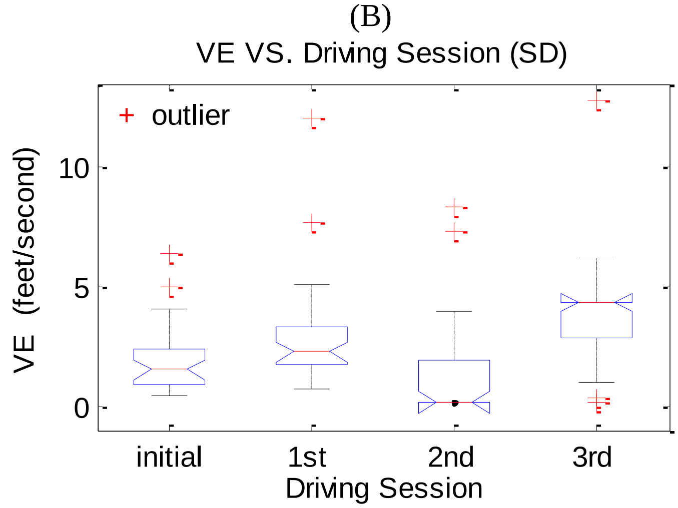


(C)

Figure 10 Inter-session variations of (A) means of LV, (B) means of VE, and (C) Standard deviation of VE

5.3 Additional analysis

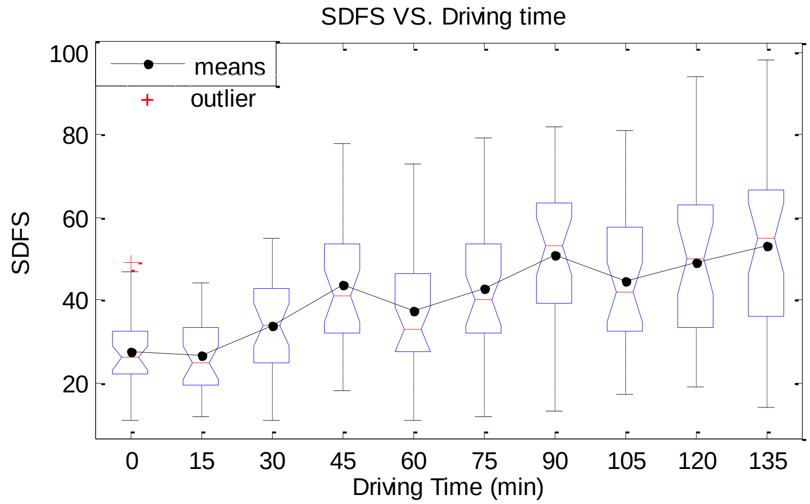
Significant overall changes and inter-sessional variations have been observed for the SDFS, residual driver capacity, the SSS, and three driving performance variables. In this section, variations within 15-minute interval are examined. Then the co-relationship between subjective fatigue levels and driving performance are examined.

5.3.1 15-minute variation

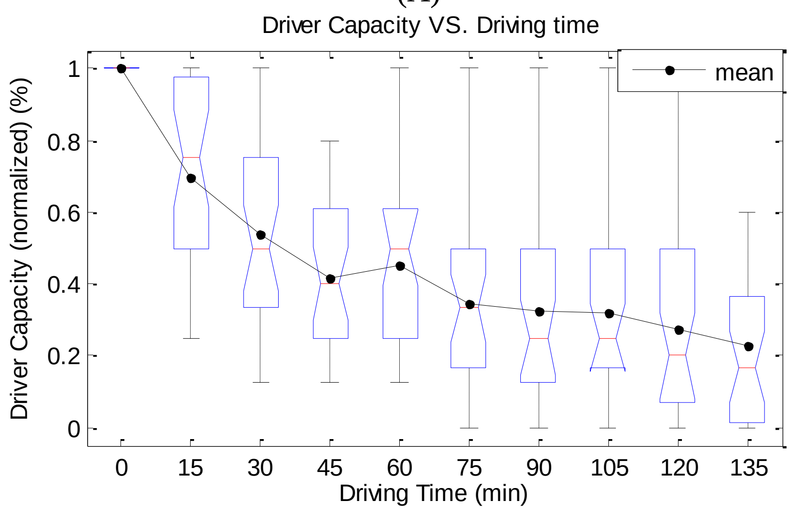
To better understand the mechanism of development of subjective driver fatigue, variations of the SDFS and normalized residua driver capacity have been examined with a 15-minute time interval.

SDFS. DFQ has been administered ten times throughout the experiment, and ten SDFS have been obtained for each subject. The group average of SDFS is plotted against driving time in in Figure 11(A). An overall trend of increase in the SDFS with time can be clearly observed from the plot. A one-way ANOVA has been used, and multi-comparison has been performed. The result shows that SDFS increased significantly with time [$F(3,123) = 10.62$, $p = 2.6956E-14$].

Although no significance has been found within any 15-minute time interval, significances have been observed on variations of the SDFS within some 30-minute time intervals. For example, the group means of SDFS are 26.8 at *t=15 min*, and 43.7 at *t=45* min, suggesting a significant increase of 16.9 after the 30-minute simulated driving task.



(A)



(B)

Figure 11 (A) SDFS against driving time, (B) normalized residual driver capacity against driving time

It is also worth noticing that the group means of SDFS showed a trend of decrease at each of the three intervals: 0 – 15, 45 – 60, and 90 – 105 minute intervals. The initial SDFS decrease between $t = 0$ and $t = 15$ min may suggest that the driving task provides stimulation to the subjects at the beginning of the experiment. As a result, the alertness increases under this stimulation for a short period of time. However, with further repeating driving tasks, the prolonged simulated driving task induces driver fatigue gradually. On the other hand, the group means of SDFS also decrease at 45 – 60 and 90 – 105 minute intervals, which include the two short breaks (less than 5 minutes) between the driving sessions. These two decreases in the SDFS suggest the recovery resulted from the two short breaks after each driving session.

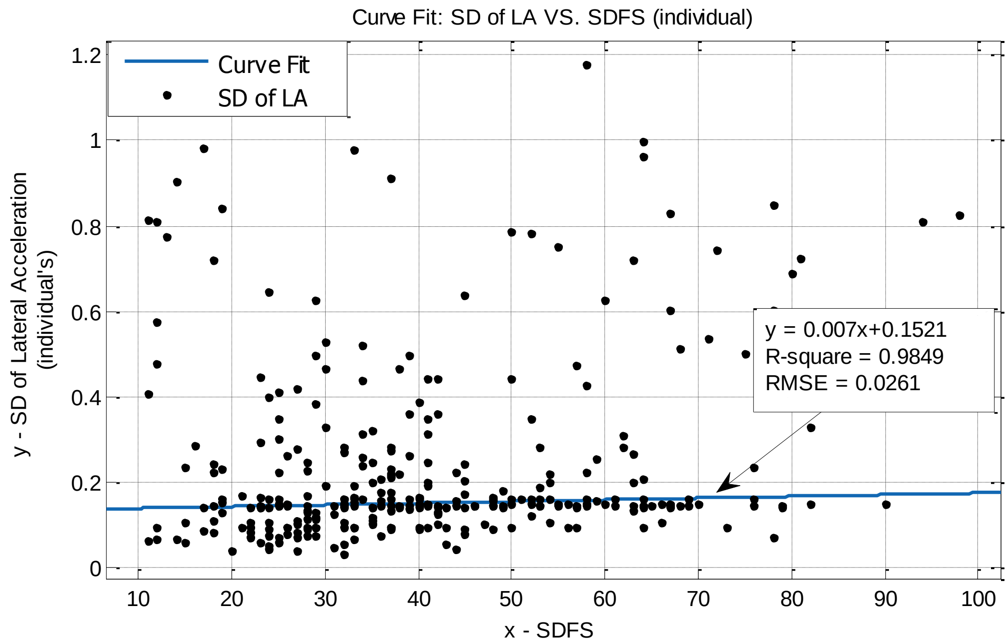
Residual driver capacities. Normalized residual driver capacities have also been obtained ten times for each subject. A similar analysis has been performed for the normalized residua driver capacity. The group averages are plotted in Figure 11. The result of One-way ANOVA shows that normalized residual driver capacity decreases significantly with time [$F(3,123) = 34.67$, $p = 1.2959E-41$]. A recovery effect is also indicated by the increase in normalized residual driver capacity after the short break between the 1st and the 2nd driving sessions.

5.3.2 Co-relationship

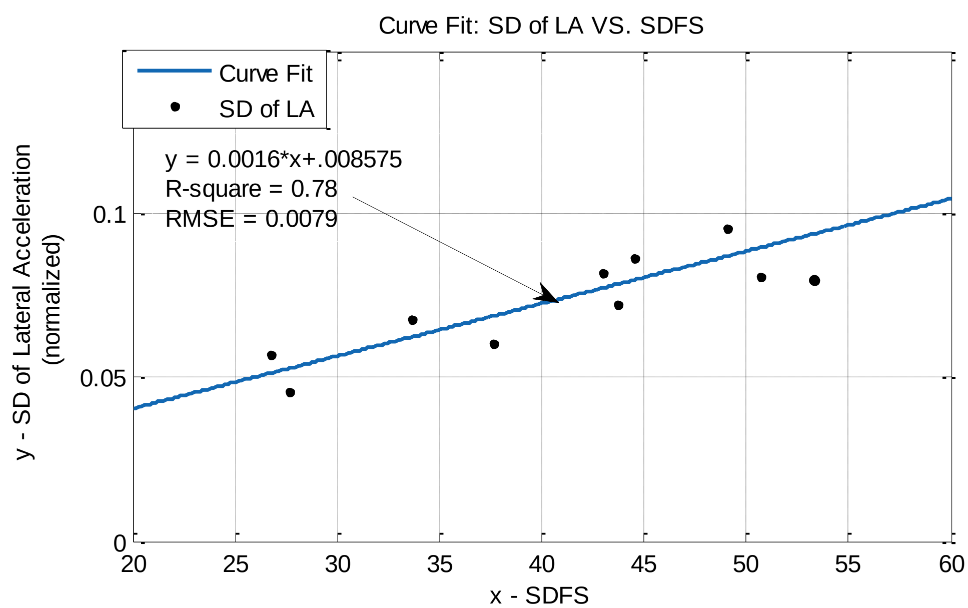
It is of interest in finding out how driver fatigue levels indicated by the SDFS are related to the driving performance. From previous investigations, it has been found that both the SDFS and driving performance change with time, and some variables of driving performance had similar trends as the SDFS. Therefore, each of 16 driving performance variables were plotted against the SDFS values. For example, the plot of SD of LA against the SDFS was given in Figure 12 (A). However, due to large individual differences, scattered points were observed. It was difficult to conclude a relationship between the SDFS and each of the driving performance parameters, although some of the curve fits, such as the one shown in Figure 12 (A), showed trends of increase with the increased SDFS. For the current experiment, we are more interested in the group change;

the group mean of SDFS was compared with the group mean of each of the 16 driving performance parameters. These group means were helpful in reducing individual differences. After investigating all the 16 driving performance variables against the SDFS, one variable – normalized standard deviation of lateral acceleration (LA) has shown a linear co-relationship with the SDFS. This mathematical co-relationship between the normalized standard deviation of LA and the SDFS are described using a curve fit as shown in Figure 12 (B), plotting the group averages of standard deviation of LA against the SDFS.

The two variables have been used in the curve fit. The first variable is the SDFS (labeled as x in the plot). The second variable is the normalized standard deviation of LA (labeled as y in the plot). Due to the individual difference in driving skills, the standard deviations of LA are quite different among individual subjects. Therefore, the normalized standard deviations are used to reduce individual difference. This has been done by dividing an individual subject's standard deviations of LA by the maximum value of these standard deviations. After this performance, the normalized standard deviations of LA then become values between 0 and 1. The standard deviation of LA can reflect both the driver ability to maintain required lateral position and fatigue information. An increase in the standard deviation of LA indicates a larger variation of LA. In other words, the lateral acceleration becomes less stable because of a degradation of driving performance. As shown in Figure 12, a straight line indicates that the standard deviations of LA increase with the increases of SDFS. It is reasonable to expect that driving performance would be impaired with increased subjective fatigue level.



(A)



(B)

Figure 12. Curve fit for standard deviation of lateral acceleration (A)individual, and (B) normalized group mean vs. subjective scores

5.3.3 Multi-dimensional subjective fatigue and driving performance

To avoid driver fatigue related accidents, drivers should be able to identify fatigue levels early. This requires a driver fatigue monitoring system that can numerically estimate driver states. Although, many researchers have suggested various methods to qualitatively identify driver fatigue, currently there is no effective system that can quantitatively measure driver fatigue. This explains why driver fatigue detecting/warning devices have not been implemented popularly in modern vehicles. In the computerized driving simulation lab, subjective driver fatigue was quantified using a questionnaire. Driving performance was also recorded to measure variations of speed, steering wheel rate, etc.

In the previous sections, the results show that the SDFS increases gradually with driving time, indicating driver fatigue becomes more severe with prolonged driving. Meanwhile, driving performance deteriorated, indicated by the increase in variation of speed, steering wheel rate, lane position and heading angles. More importantly, a linear relationship has been observed between the SDFS and standard deviation of LA (as shown in Figure 12). This mathematical relationship suggests that it is possible to predict driving performance, if the SDFS is known, and vice versa. That is, by monitoring the SDFS and/or driving performance, it is possible to determine whether the driver's state is suitable to continue the driving task.

However, it is not enough to make a decision just based on these two parameters, the SDFS and the standard deviation of LA. Since driver fatigue assessment can be considered as a multi-dimensional measure [11, 43, 97], sub scores can be calculated to reflect the multi aspects of driver fatigue in detail. Five sub scores have been calculated from the twelve items listed in Table 10. These sub scores are (1) physical fatigue symptoms, (2) driving behaviors, (3) perception, (4) tiredness, and (5) capacity consumption.

The sub score, physical fatigue symptom, includes items No.4, No.8~11 listed in Table 10, which evaluate severity of headache, sore feet, backache, joint stiffness, and numbness. This sub score is denoted as ${}_{t}pfs^{m}$, and is calculated using Equation 7. The sub score, driving behaviors, include items No. 6 and No.7, which describes the subjective tendencies to pass a leading vehicle and pull over for a rest. This sub score is denoted as ${}_{t}dbh^{m}$, and is calculated using Equation 8. The sub score, perception, includes items No.1 and No.5, which report feelings of driver fatigue interfering with safe driving, and feelings of eye strain. This sub score is denoted as ${}_{t}per^{m}$ and is calculated using Equation 9. The sub score, tiredness, include items No.2 and No.3, which reflect sleepiness and ability to concentrate. This sub score is denoted as ${}_{t}tir^{m}$ and is calculated using Equation 10. The last sub score, capacity consumption, is obtained from the item No.12, which reports driver capacity. This sub score is denoted as ${}_{t}cap^{m}$; it is the ratio of the difference between the maximum capacity and the current driver capacity to the maximum capacity. The maximum capacity is the maximum value of all the ten values reported by an individual subject for the item No.12. Equation 11 is used to calculate capacity consumption. All sub scores range from 0 to 1, and a larger value of the sub score indicates the higher level of driver fatigue.

$${}_{t}pfs^{m} = \left({}_{t}Q_{4}^{m} + {}_{t}Q_{8}^{m} + {}_{t}Q_{9}^{m} + {}_{t}Q_{10}^{m} + {}_{t}Q_{11}^{m} \right)/50 \qquad \text{Equation 7}$$

$${}_{t}dbh^{m} = ({}_{t}Q_{6}^{m} + {}_{t}Q_{7}^{m})/20 \qquad \text{Equation 8}$$

$${}_{t}per^{m} = ({}_{t}Q_{1}^{m} + {}_{t}Q_{5}^{m})/20 \qquad \text{Equation 9}$$

$${}_{t}tir^{m} = ({}_{t}Q_{2}^{m} + {}_{t}Q_{3}^{m})/20 \qquad \text{Equation 10}$$

$${}_{t}cap^{m} = ({}_{*}Q_{12}^{m} - {}_{t}Q_{12}^{m})/{}_{max}Q_{12}^{m} \qquad \text{Equation 11}$$

where

${}_{t}Q_{n}^{m}$ = the score of the n^{th} item in the questionnaire for m^{th} subject at the time t, and $1 \leq n \leq 12$

${}_{t}pfs^{m}$ = the sub score of physical fatigue symptom

${}_{t}dbh^{m}$ = the sub score of driving behaviors

${}_{t}per^{m}$ = the sub score of perception

${}_{t}tir^{m}$ = the sub score of tiredness

${}_{t}cap^{m}$ = the sub score of capacity consumption

${}_{max}Q_{12}^{m}$ = the maximum value of ${}_{t}Q_{12}^{m}$ (with t = [0, 15,30, … , 135]

The five sub scores are plotted in a radar diagram, shown as the purple pentagons in Figure 13. This radar diagram of subjective score shows several characteristics of driver fatigue. It can help the driver to identify the type of fatigue. Generally speaking, fatigue caused by sleep debt is different from fatigue caused by mental overload (or underload). For example, high sleepiness and low alertness are usually related to fatigue caused by sleep debt. Low sleepiness, low alertness, and significant change in fatigue symptom are usually associated with fatigue caused by mental overload [41].

Driving performance also has multiple variables reflecting different driver abilities, such as steering wheel control, lateral position control, etc. From the previous analysis on driving performance variables, it can be seen that the overall changes are significant for the standard deviations of (1) steering wheel angel input, (2) yaw rate, (3) lateral velocity, (4) lateral acceleration, and (5) longitudinal velocity. More importantly, the normalized standard deviation of LA linearly increases with increases in the SDFS. Each of the other variables can also be normalized by using the corresponding maximal values of each variable as a normalizing factor. These normalized variables are obtained from Equation 12 ~ Equation 16.

These normalized variables can also be plotted as a radar diagram, shown as the orange-red pentagon in Figure 14. It shows the characteristics of driving performance in multi dimensions. It can be seen from the plot that the initial driving performance does not approach zero, indicating each driving performance variable has non-zero variance even at very low fatigue levels. It is worth to notice that the maximum value of each variable is the value at the end of the experiment, and a full pentagon has been obtained for the final driving performance as shown in Figure 14 (B). From these two multidimensional plots for subjective fatigue and driving performance, it is possible to develop devices to numerically measure driver fatigue and performance simultaneously and determine whether driving performance is deteriorated by increased driver fatigue.

$${}_{t}\hat{\sigma}_{sa}^{m} = {}_{t}\sigma_{sa}^{m} \,/\, {}_{max}\sigma_{sa}^{m} \qquad \text{Equation 12}$$

$${}_{t}\hat{\sigma}_{yr}^{m} = {}_{t}\sigma_{yr}^{m} \,/\, {}_{max}\sigma_{yr}^{m} \qquad \text{Equation 13}$$

$${}_{t}\hat{\sigma}_{lv}^{m} = {}_{t}\sigma_{lv}^{m} \,/\, {}_{max}\sigma_{lv}^{m} \qquad \text{Equation 14}$$

$${}_{t}\hat{\sigma}_{la}^{m} = {}_{t}\sigma_{la}^{m} \,/\, {}_{max}\sigma_{la}^{m} \qquad \text{Equation 15}$$

$${}_{t}\hat{\sigma}_{ve}^{m} = {}_{t}\sigma_{ve}^{m} \,/\, {}_{max}\sigma_{ve}^{m} \qquad \text{Equation 16}$$

where

${}_{t}\hat{\sigma}_{sa}^{m}$ = the normalized standard deviation of SA for m^{th} subject at the time t

${}_{max}\sigma_{sa}^{m}$ = the maximum value of ${}_{t}\sigma_{sa}^{m}$, (with t = [0, 15,30, … , 135])

${}_{t}\hat{\sigma}_{yr}^{m}$ = the normalized standard deviation of YR

${}_{max}\sigma_{yr}^{m}$ = the maximum value of ${}_{t}\sigma_{yr}^{m}$

${}_{t}\hat{\sigma}_{lv}^{m}$ = the normalized standard deviation of LV

${}_{max}\sigma_{lv}^{m}$ = the maximum value of ${}_{t}\sigma_{lv}^{m}$

${}_{t}\hat{\sigma}_{la}^{m}$ = the normalized standard deviation of LA

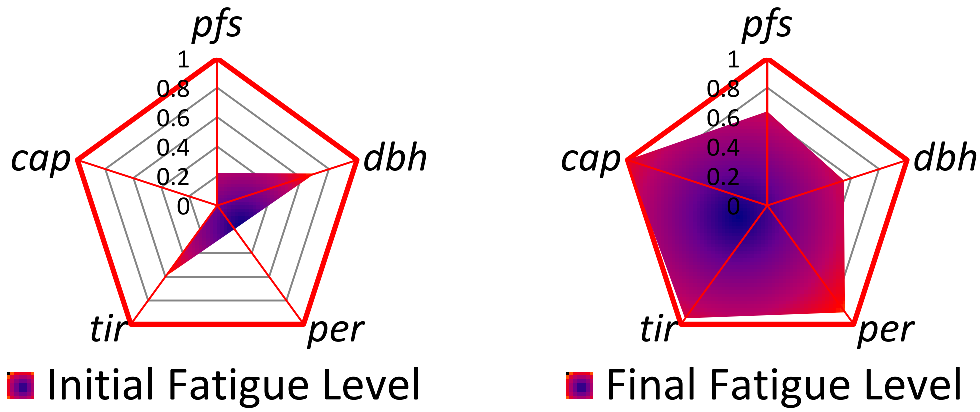
${}_{max}\sigma_{la}^{m}$ = the maximum value of ${}_{t}\sigma_{la}^{m}$

${}_{t}\hat{\sigma}_{ve}^{m}$ = the normalized standard deviation of VE

${}_{max}\sigma_{ve}^{m}$ = the maximum value of ${}_{t}\sigma_{ve}^{m}$

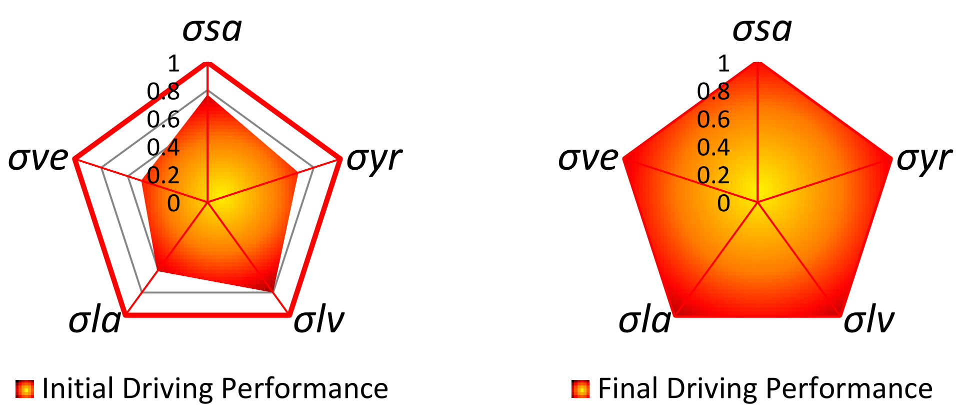
It also helps us to distinguish the type of fatigue and make correct suggestions to the driver. If fatigue is related to sleep debt, the driver should stop driving and sleep well to get recovered. If fatigue is related to mental overload, the driver may activate some advanced driving assistance system (such as lane keeping function, collision avoidance function, etc.) to reduce mental workload, or take a short break to recover from driver fatigue. In our experiment, it was also found that after prolonged simulated driving, a 3-minutes short break helped the driver to recover. Driving performance improved significantly and subjective fatigue score decreased.

Combined with other existing advanced driving assistance systems, it is believed that monitoring the parameters introduced here can help drivers notice increased fatigue level and deteriorated driving performance. These multidimensional indicators for subjective driver fatigue and driving performance may help drivers make wise actions during driving tasks and drive safely without fatigue. For example, the driver can choose an effective fatigue countermeasure to reduce fatigue levels. Many fatigue countermeasures have been applied by drivers who work for prolonged work shifts. The next experiment will examine the effectiveness of two of most frequently applied fatigue countermeasures.



(A) (B)

Figure 13. A typical multidimensional fatigue change of an individual driver. *pfs: physical fatigue symptom; dbh: driving behaviors; per: perception; tir: tiredness; cap: capacity consumption*



(A) (B)

Figure 14 A typical multidimensional driving performance change of an individual driver. *σsa: standard deviation of SA; σyr: standard deviation of YR; σlv: standard deviation of LV; σla: standard deviation of LA; σve: standard deviation of VE*

5.4 Divided attention test

Reaction time was recorded for the divided attention test. It was expected that reaction time would increase with increased fatigue levels. However, when the reaction time was plotted against driving time, as shown in Figure 15, reaction time almost was decreasing all the way from beginning to the half way of the experiment, and then remained constant until the end of the experiment.

This result is very different from the expectation and the observation from other researchers [102]. The reduction of reaction time at the first half part of the experiment may reflect the learning effects. One of the possible reasons for this unexpected result was that the divided attention test was taken during the driving task. The reaction time test was often taken separately by drivers in other experiments and was only influenced by fatigue levels, not other factors such as mental workload. However, in the current experiment, the reaction time was influenced by many factors, including fatigue levels, mental workload, complexity of road scenarios, etc. On the other hand, there was no visual or auditory cue signaling reaction test onset, and the subject had no clue when the test would start. This also made the subjects take more time to response to the triggering signal. Therefore, the divided attention test without a signaling cue, such as the one used in the current experiment, is not a good indicator of fatigue levels, if taken while driving.

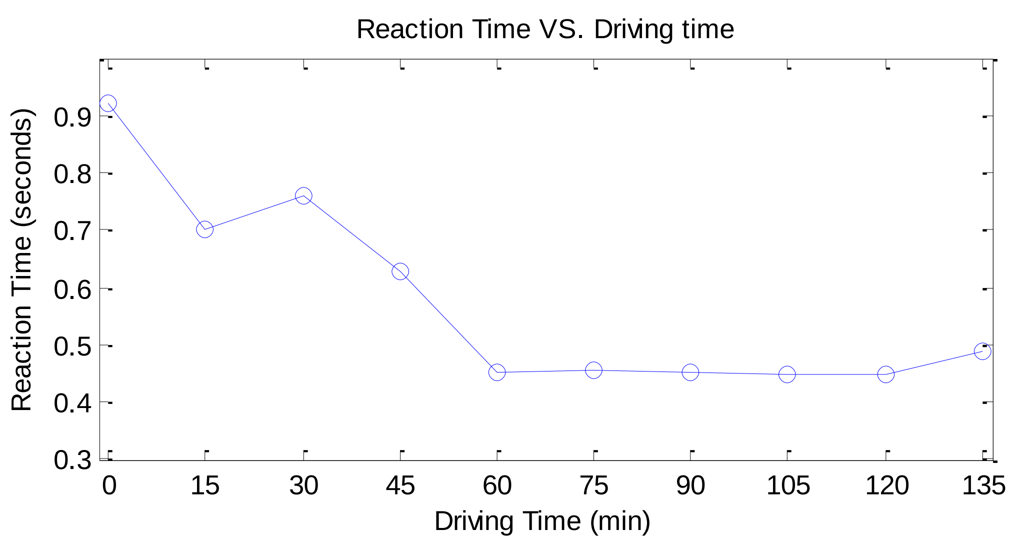


Figure 15 Reaction times against driving time

Chapter 6 The Second Experiment (*Data Analysis*)

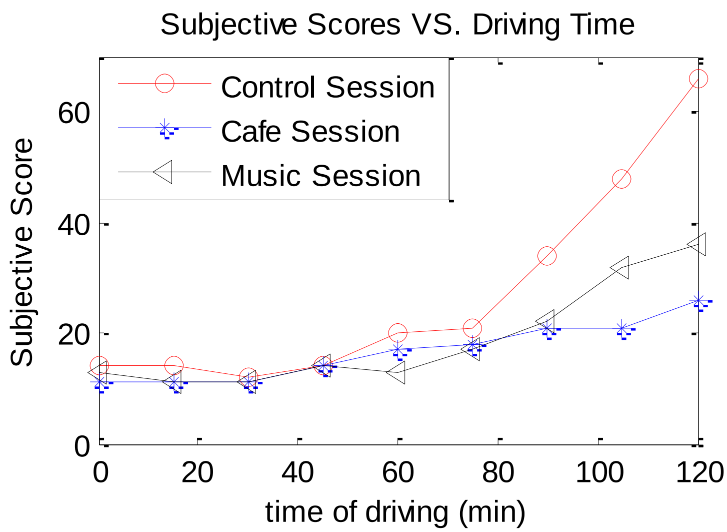
The second experiment results are presented in this chapter. One-way ANOVAs were used to examine whether the SDFS and driving performance were different at the beginnings of the control, caffeine, and music sessions. The independent variables were types of driving session (control, caffeine, and music) and driving time. Dependent variables were the SDFS, driving performance measurements, and brain activity represented by EGG signals. Multi-comparisons were performed using the Tukey test [100]. Then, a series of paired student *t*-tests were performed to check whether (1) changes in SDFS and driving performance and brain activities were significant after 120-minute driving sessions, and (2) differences in increments of the SDFS and driving performance and brain activities were significant between any two of the driving sessions. All analyses were conducted at the .05 significance level unless otherwise noted. A part of the results in the second experiment was published in [103].

6.1 Subjective Assessment (SDFS)

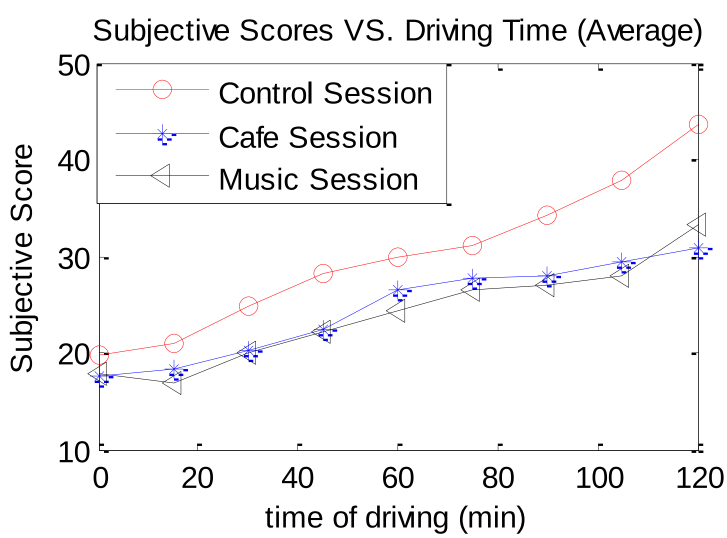
In the current experiment, the questionnaire has been administered to estimate driver fatigue levels for three driving sessions. The variations of the SDFS with time were examined for each driving session. Then the differences among the driving sessions were also examined to check the effectiveness of each fatigue countermeasures.

Each subject completed three driving sessions: control, caffeine, and music sessions. Right before starting each of the sessions, the subject answered the questionnaire in writing; during the driving session, the subject verbally answered the questionnaire after driving for every fifteen minutes; then at the end of the experiment (after driving for 120 minute) the subject answered the last questionnaire in writing again. The subject administered the questionnaire nine times for each driving session, two in writing (before and after driving session) and seven verbally (during the driving session). In total, a subject who completed all three driving sessions completed the questionnaire twenty-seven times.

The variation in subjective driver fatigue scores of a typical subject is shown in Figure 16(A). The initial states of the subject at the beginnings of the three driving sessions were similar. This was indicated by the similar low the SDFS at the beginnings of three driving sessions: 14 for control session, 11 for caffeine session, and 12 for music session. Since the subjects were asked to start the three driving sessions at the same time of the day and with the similar states, small variations in the SDFS at the beginnings of three driving sessions were not surprising. Indeed, when one-way ANOVAs were used to examine variations in the initial the SDFS of all twenty subjects, no significant difference has been found among the control, caffeine, and music sessions [F(2,57,59) = 0.6, p = 0.5526]. The results are shown in Figure 17. This indicates that each subject started all the driving sessions at similar fatigue levels. This is also shown in Figure 16 (B), a plot of the average SDFS vs. driving time.



(A)



(B)

Figure 16 SDFS increases with driving time (A) SDFS for an individual subject; (B) average SDFS for all subjects

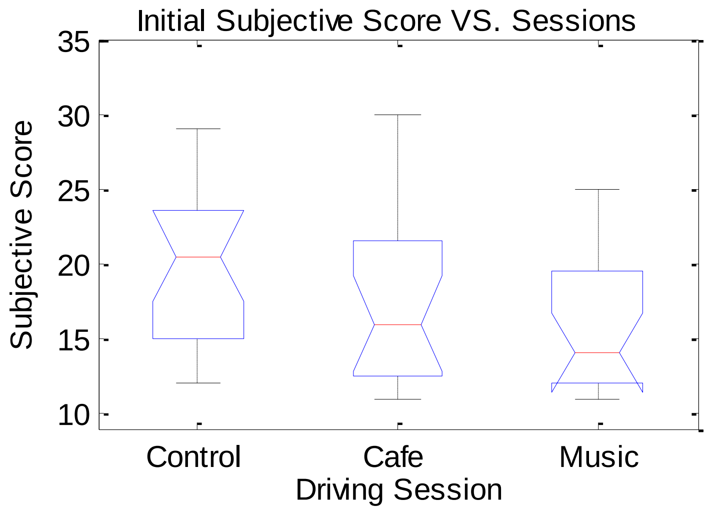


Figure 17 one-way ANOVA results for initial SDFS of three driving sessions

Although the subjects started driving sessions at similar low fatigue levels, their SDFS were different after completing three sessions, all of which consisted of 120 minutes of simulated driving. From Figure 16, it can be seen that after 120 minutes simulated driving, the SDFS was increased from initial low levels. The scores at the beginning and the end of each driving session were compared using paired student t-tests. It was observed that the SDFS increased significantly after completing (1) the control session [p= 7.76E-6, t = -5.74, CI=(-∞, -16.6)] , (2) the caffeine session [p=3.87E-5, t = -5.01, CI=(-∞, -8.78)], and (3) the music session [p=1.46E-5, t = -5.45, CI = (-∞, -10.5)]. A one-way ANOVA was used to examine whether these overall increases in the SDFS were significant among control, caffeine, and music sessions or not. The results, as shown in Figure 18, suggested that inter-session differences among three driving sessions were not significant for the SDFS increases [F(2,57,59)=2.81, p=0.0688]. A multi-comparison was performed using the Tukey test, also suggesting no significant differences between any two driving sessions. However, paired student t-tests revealed that (1) the increase in the SDFS in control sessions were significantly larger than in caffeine sessions [p=0.0192, t = 2.56, CI=(1.89, 18.8)], (2) the increase in SDFS in control sessions were significantly larger than in music sessions [p=0.0257, t = 2.4204, CI=(1.13, 15.6)], and (3) the increase in SDFS were not significantly different between caffeine and music sessions [p=0.535, t = -0.6313, CI=(-8.63, 4.63)]. The different results of the one-way ANOVA and repeated student t-tests were probably caused by losing the power of repeated measure of the multiple comparisons.

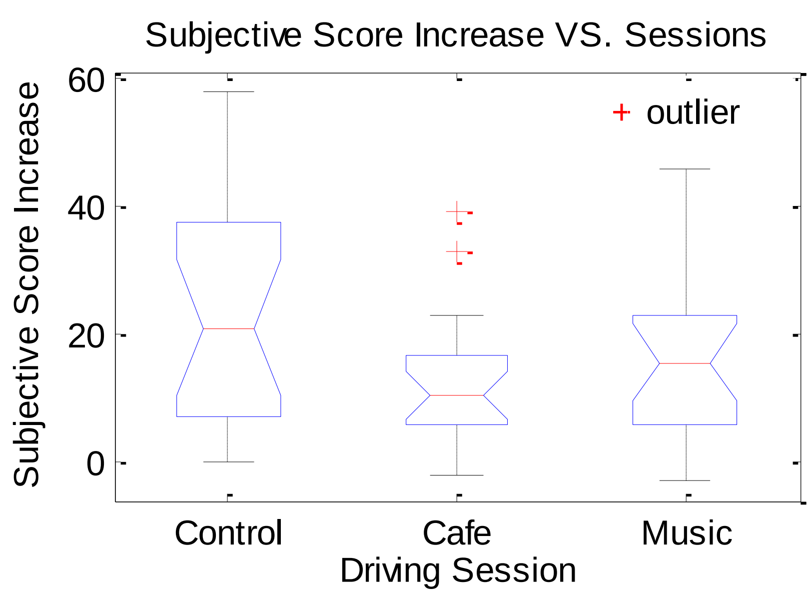


Figure 18 one-way ANOVA results for the SDFS increase in three driving sessions

In general, each driver started the driving sessions at relatively low but similar SDFS. After each of the sessions, the SDFS increased significantly. On the other hand, the increment was largest for control sessions, medium for music sessions, and smallest for caffeine sessions. The increments of the SDFS after caffeine and music sessions were significantly less than after control sessions. The increments were not significantly different between the caffeine and music sessions. The results suggested that the two fatigue countermeasures, consuming caffeine and listening to music, had similar positive effects on reducing subjective fatigue levels. However, it is also important to examine whether these two fatigue countermeasures can help drivers maintain driving performance.

6.2 Driving Performance

Driving performance was estimated through 16 parameters, as in the 1st experiment. These parameters were examined to determine (1) whether initial driving performance was significantly different among three driving sessions, (2) whether driving performance deteriorated after each session, and (3) whether the variation in driving performance was significantly different between any two of three sessions.

6.2.1 Initial difference

The steering wheel angle input (SA) was recorded at a frequency of 20Hz. The initial SA for the m^{th} participant was denoted as ${}_{initial}sa_n^m$ *(m=1~20, n=1~6000)*, recorded in the first 5-minute LKT. The mean initial SA of the m^{th} participant, denoted as $\overline{sa^m}$, was calculated using Equation 3. The standard deviation of the initial SA, denoted as σ_{sa}^m, was calculated using Equation 4. The mean of the SA was then calculated for all twenty drivers using Equation 5, and denoted as $\overline{SA}$. The mean standard deviation of the SA was calculated using Equation 6, and denoted as $\overline{\sigma_{sa}}$. Similarly, values of $\overline{SA}$ and $\overline{\sigma_{sa}}$ were calculated for the last 5-minute LKT for each driving session. The results of initial and final $\overline{SA}$ were plotted for the control, caffeine, and music sessions in Figure 19 on the left-hand side, and and $\overline{\sigma_{sa}}$ was plotted on the right hand side. Twenty drivers' $\overline{sa^m}$ were calculated for each session for the first LKT. A one-way ANOVA was used to examine whether $\overline{sa^m}$ were different among three driving sessions. The result showed that the means of SA were not significantly different among control, caffeine, and music sessions [F(2,57,59)=0.44, p=0.65]. Multi-comparison was performed using the Tukey test, also suggesting no significant differences between any two of the three driving sessions.

Twenty σ_{sa}^m were calculated for each session for the first LKT and analyzed using a one-way ANOVA. The result showed that the standard deviation of initial SA was not significantly different among three sessions [F(2,57,59)=0.2, p=0.82]. Multi-comparison indicated that there were no significant differences between any two of the control, caffeine, and driving sessions.

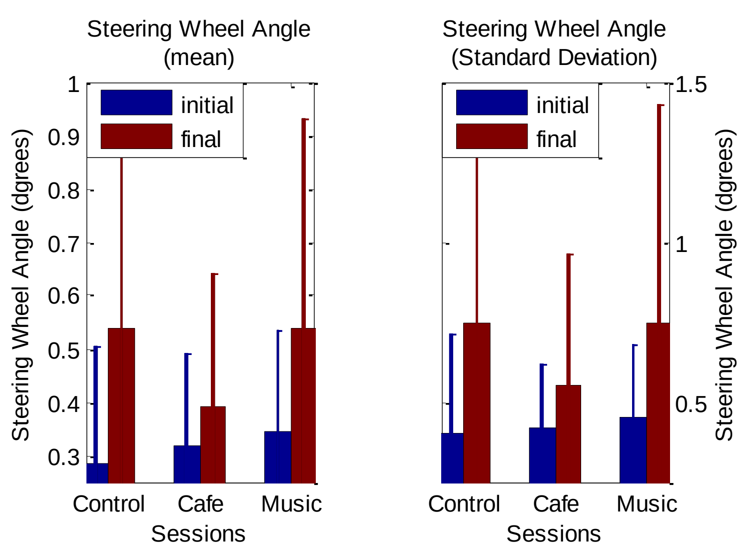


Figure 19 mean values and standard deviations of SA at beginnings and ends of three sessions

Similar statistical analyses were performed for the other 14 parameters (means and standard deviations of SR, etc.). The results for these parameters are shown in Figure 23 – Figure 29 . The *p* values of one-way ANOVAs were summarized in Table 14. Combined with multi-comparison, the results revealed that none of the parameters showed significant differences between any two of three sessions. This suggests that, for each driver, there was virtually no difference in driving performance at the beginnings of control, caffeine, and music sessions. This was not surprising, because for each subject, there was no significant difference in the SDFS at the beginnings of the three sessions.

Table 14. *p* values of one-way ANOVA for initial driving performance parameters

	Steering wheel control			*Lateral position control*			*Speed control*	
	SA	SR	YR	LP	LV	LA	VE	AC
mean	0.65	0.63	0.57	0.69	0.57	0.55	0.53	0.15
SD	0.82	0.53	0.73	0.25	0.74	0.66	0.40	0.22

6.2.2 Deterioration of driving performance

Although driving performance was virtually identical at the beginnings of three sessions, both means and standard deviations of SA increased after completing each session, as shown in Figure 19. The results of the paired student *t*-test showed that the increase in mean of SA was (1) significant after the control session [p=0.00005, t = -5.19, CI=(-0.35, -0.15)], (2) not significant after the caffeine session [p=0.09, t = -1.76, CI = (-0.17, 0.01)], and (3) significant after music session [p=0.01, t = -2.77, CI = (-0.33, -0.05,]. The results of the paired student *t*-tests on the standard deviation of SA showed that variance of steering wheel angle input increased significantly after control session [p=0.0009, t = -3.95 , CI = (-0.53, -0.16)], not significantly after caffeine session [p=0.091, t = -1.78 , (-0.29, 0.02)], and significantly after music session [p=0.038, t = -2.23 , (-0.57, -0.018)]. Similar statistical analyses were performed for other 14 driving performance parameters, and the p values of the paired student t-test were summarized in Table 15, with parameters showing significant change highlighted. The results showed that 13 of the 16 parameters showed significant change after completing control sessions, 9 parameters showed significant change after completing music sessions, and only 6 parameters showed significant change after completing caffeine sessions.

Table 15. ***p*** values of paired student *t*-test for deterioration

	Steering wheel control			*Lateral position control*			*Speed control*	
	SA	SR	YR	LP	LV	LA	VE	AC
	Control Session							
mean	**.000**	**.002**	**.000**	.159	**.007**	**.000**	.078	**0.03**
SD	**.000**	**.000**	**.000**	**.039**	**.009**	**.001**	.111	**.030**
	Music session							
mean	**.012**	.086	**.017**	.197	**.011**	**.024**	.450	.054
SD	**.038**	.067	**.047**	**.013**	**.022**	.054	.536	**.037**
	Caffeine session							
mean	.093	.752	.131	.299	**.025**	.222	.719	**.008**
SD	.091	.204	.115	**.009**	**.026**	.184	**.012**	**.006**

Further observation revealed that increments in mean SA, denoted as $\delta_{\mathrm{sa}}^{\mathrm{m}}$,were greatest for the control session (0.25 degrees), medium for the music session (0.19 degrees), and smallest for the caffeine session (0.08 degrees). Furthermore, the increment in standard deviation of SA, denoted as $\Delta_{\mathrm{sa}}^{\mathrm{m}}$ was greatest for the control session (0.3457 degrees), medium for music sessions (0.296 degrees), and smallest for the caffeine session (0.1339 degrees). The increments of all 16 parameters were listed in Table 16. The results showed that 112 increments were greatest for control session, medium for music session, and smallest for caffeine session. Only 5 parameters showed a different trend (increments in the means of lateral velocity and longitudinal acceleration, standard deviations of lateral position, standard deviation of velocity, and the standard deviation of acceleration).

Table 16. increment of driving performance parameters

	Steering wheel control			*Lateral position control*			*Speed control*	
	SA	SR	YR	LP	LV	LA	VE	AC
	Increment in mean							
control	0.25	0.005	0.002	0.89	**0.11**	0.11	1.73	**0.18**
music	0.19	0.003	0.001	0.81	**0.13**	0.09	0.78	**0.09**
caffeine	0.07	0.000	0.000	0.17	**0.08**	0.03	0.42	**0.21**
	Increment in SD							
control	0.35	0.015	0.002	**0.39**	0.17	0.16	**1.21**	**0.28**
music	0.30	0.010	0.002	**0.43**	0.17	0.15	**0.31**	**0.21**
caffeine	0.13	0.004	0.001	**0.44**	0.10	0.05	**2.39**	**0.31**

To better illustrate the result, the relative increments of each parameter were calculated. For example, to obtain the relative increment of the steering wheel angle, the group mean of the control session was set as a reference, and the group means of δ_{sa}^{m} in the three driving sessions were divided by the reference and the relative increments were presented as percentages: 100% for the control session, 76% for the music session, and 28% for the caffeine session. In other words, the increment of the mean steering wheel angle input was greatest for the control session. The increment in the music session was medium, which was 76% of the increment in the control session. The increment was smallest in the caffeine session, only 28% of that in the control session. For the standard deviation of steering wheel angle input, also setting the group mean of the control session as the reference, the group means of Δ_{sa}^{m} in the three driving session were divided by the reference to obtain the relative increments. The relative increment was 100% for the control session, 86% for the music session, and 37% for the music session. The increments in the music and caffeine sessions were 86% and 37% of that in control session respectively. This also indicated that the increment of standard deviation of the steering wheel angle input was largest in the control session, medium in the music session, and smallest in the caffeine session. These are summarized in Table 17, along with the other 14 relative increments of driving performance parameters.

Table 17. Relative increment of driving performance parameters (%)

	Steering wheel control			***Lateral position control***			***Speed control***	
	SA	SR	YR	LP	LV	LA	VE	AC
	(A) Relative increment in mean							
control	100	100	100	100	**100**	100	100	**100**
music	76	60	81	91	**118**	82	45	**50**
caffeine	28	8	31	19	**73**	27	24	**117**
	(B) Relative increment in SD							
Control	100	100	100	**100**	100	100	**100**	**100**
Music	86	67	95	**110**	100	94	**26**	**75**
caffeine	37	27	36	**113**	59	31	**198**	**111**

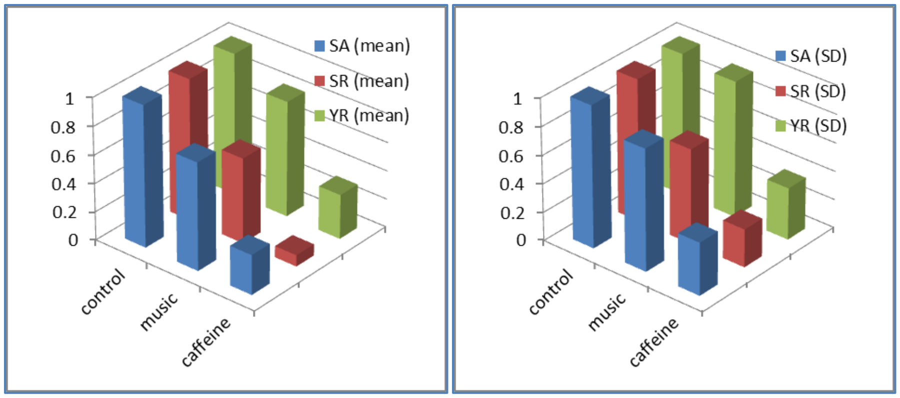
The first three columns contain the relative increments of the first group of parameters: means and standard deviations of steering wheel angle input, steering wheel rate, and yaw rate, which reflect steering wheel control ability. These relative increments of the means were plotted in Figure 20(a) and standard deviations were plotted in Figure 20(b). It clearly showed that steering wheel control ability deterierated the most in the control session, medium in the music session, and the least in the caffeine session.

The next three columns contain the relative increments of the second group of variables: means and standard deviations of lateral position, lateral velocity, and lateral acceleration, which reflect lateral position control ability. These relative increments of the means were plotted in Figure 21(a) and the standard deviations were plotted in Figure

21(b). It can be seen that 4 of the lateral position control variables showed a similar trend as the steering wheel control variables: increments in the means and standard deviations of lateral position and lateral acceleration were the greatest in the control session, medium in the music session, and the least in the caffeine session. The increments of the mean and standard deviatin of lateral velocity were greatest in the music session, medium in the control session, and least in the caffeine session.

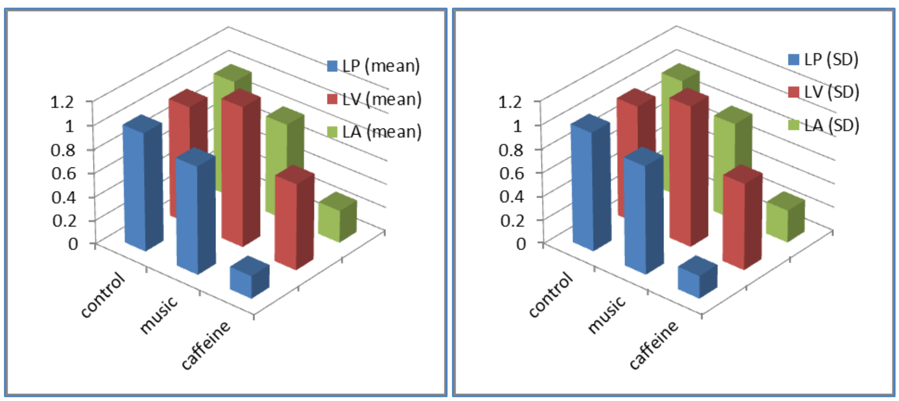
The last two columns contain the relative increments of the third group of variables: means and standard deviations of longitudinal velocity and longitudinal acceleration, which reflect speed control ability. These relative increments of means were plotted in Figure 22 (a) and the standard deviations were plotted in Figure 22 (b). The increment of the mean of longitudinal velocity was the greatest in the control session, medium in the music session, and smallest in the caffeine session. This is the same trend shown in the steering wheel control variables. The increment of other three variables (mean of the acceleration, standard deviations of velocity and acceleration) were greatest in the caffeine session, medium in the control session, and smallest in the music session.

This results suggested that driving performance deteriorated mostly after completing control sessions, moderately deteriorated after completing music sessions, and least deteriorated after completing caffeine sessions. The result implies that both consuming caffeine and listening to music have positive effects on maintaining driving performance, but consuming caffeine is more effective than listening to music.



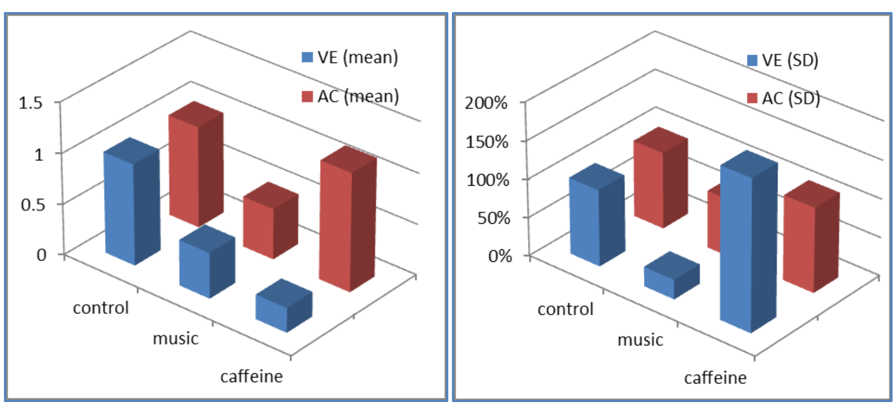
(a) (b)

Figure 20 relative increment for steering wheel control parameters: (a) the means and (b) standard deviations (SD) of steering wheel angle input (SA), steering wheel rate (SR), and yaw rate (YR)



(a) (b)

Figure 21 relative increment for lateral position control variables: (a) the means and (b) SDs of lateral position (LP), lateral velocity (LV), and lateral acceleration (LA)



(a) (b)

Figure 22 relative increment for speed control variables: (a) the means and (b) SDs of longitudinal velocity (VE) and longitudinal acceleration (AC)

6.2.3 Inter-session variation

Although both countermeasures showed positive effects on driving performance, the above results suggested that the effects were different. It is of interest in whether these differences are significant or not. A paired student *t*-test was used to compare the increments of mean SA between any two of three sessions. The results showed that the increments in mean SA were (1) significantly different between the control and caffeine sessions [p=0.005, *t* = 3.20, CI=(0.06, 0.29)], (2) significantly different between the music and caffeine sessions [p=0.03, *t* = 2.35, CI = (0.013, 0.22)], and (3) not significantly different between the control and music sessions [p=0.417, *t* = 0.83, CI = (-0.088, 0.202)]. Furthermore, the increments in the standard deviation of SA were (1) not significantly different between the control and caffeine sessions [p=0.055, *t* = 2.04, CI = (-0.0051, 0.43)], (2) not significantly different between the music and caffeine sessions [p=0.160, *t* = 1.46, CI = (-0.070, 0.39)], and (3) not significantly different between the control and music sessions [p=0.748, *t* = 0.325, CI = (-0.2701, 0.3695)]. Similar analysis was performed for the other 14 parameters, the results were shown in Figure 23 – Figure 29, and the *p* values of paired student *t*-test were summarized in Table 18.

Table 18. comparison of increments between sessions

	Steering wheel control			***Lateral position*** *control*			***Speed*** *control*	
	SA	SR	YR	LP	LV	LA	VE	AC
	Control VS. Caffeine							
mean	**.005**	**.003**	**.002**	.251	.424	**.004**	.392	.717
SD	.055	**.005**	**.033**	.776	.282	**.036**	.201	.823
	Music VS. Caffeine							
mean	**.03**	.057	**.034**	.232	.209	**.043**	.769	**.033**
SD	.160	.131	.123	.970	.276	.100	**.012**	.151
	Control VS. Music							
mean	.417	.416	.469	.928	.722	.496	.422	.285
SD	.748	.455	.889	.790	.996	.944	.314	.621

The results revealed that the increments of 7 parameters showed significant differences between the control and caffeine sessions, the increments of 5 parameters showed significant difference between the music and caffeine sessions, however, no increment of 16 parameters showed significant difference between the control and music sessions. This confirmed that effects of the two fatigue countermeasures on driving performance were different: consuming caffeine was more effective than listening to music. Although increments of 15 driving performance parameters after the music session were less than those after the control session, none of these differences was significant; suggesting that, for each driver, deterioration in driving performance was virtually not different between the control and music sessions.

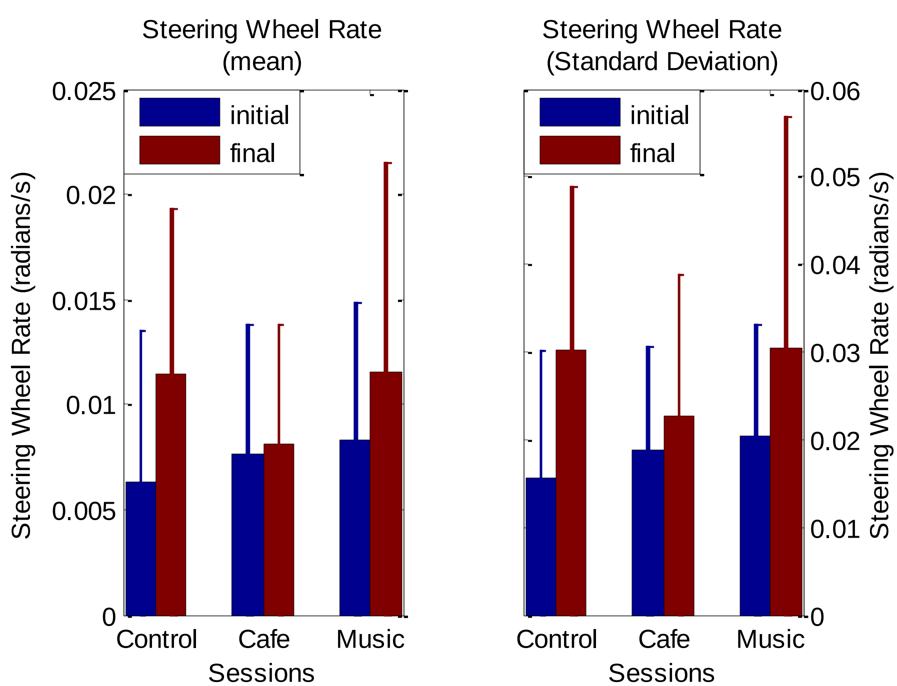


Figure 23 means and standard deviations of SR at beginnings and ends of three sessions

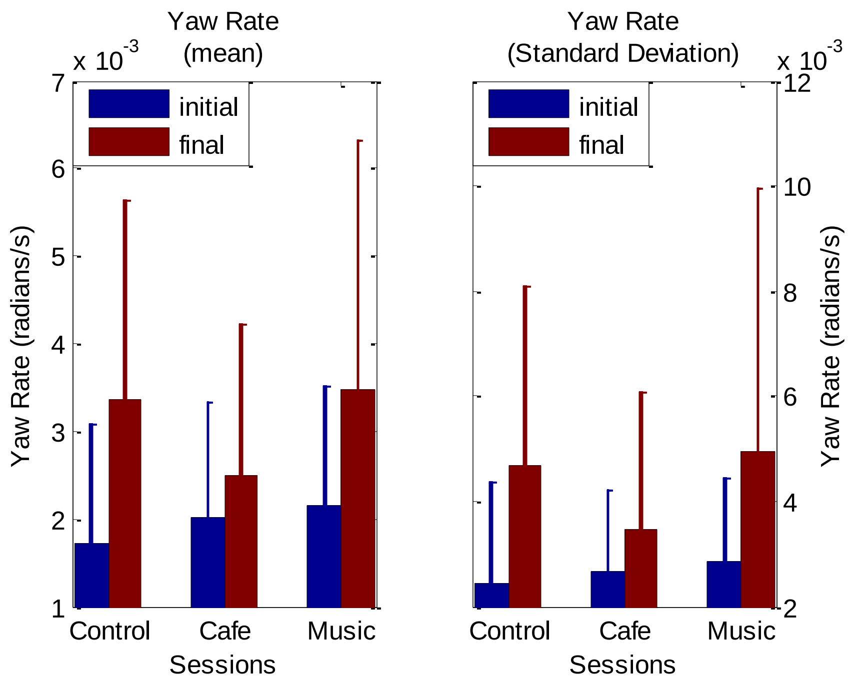


Figure 24 means and standard deviations of YR at beginnings and ends of three sessions

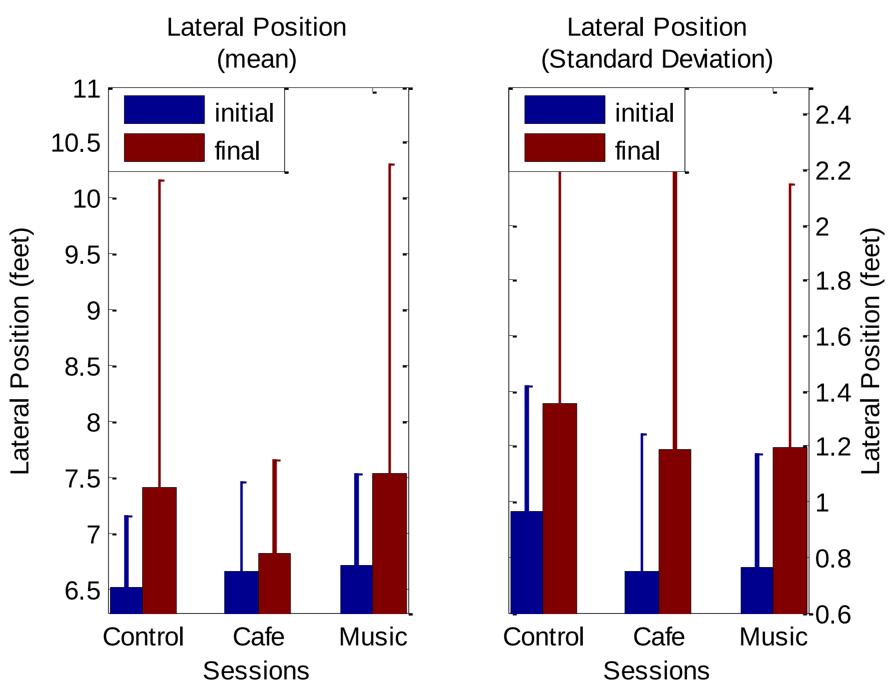


Figure 25 means and standard deviations of LP at beginnings and ends of three sessions

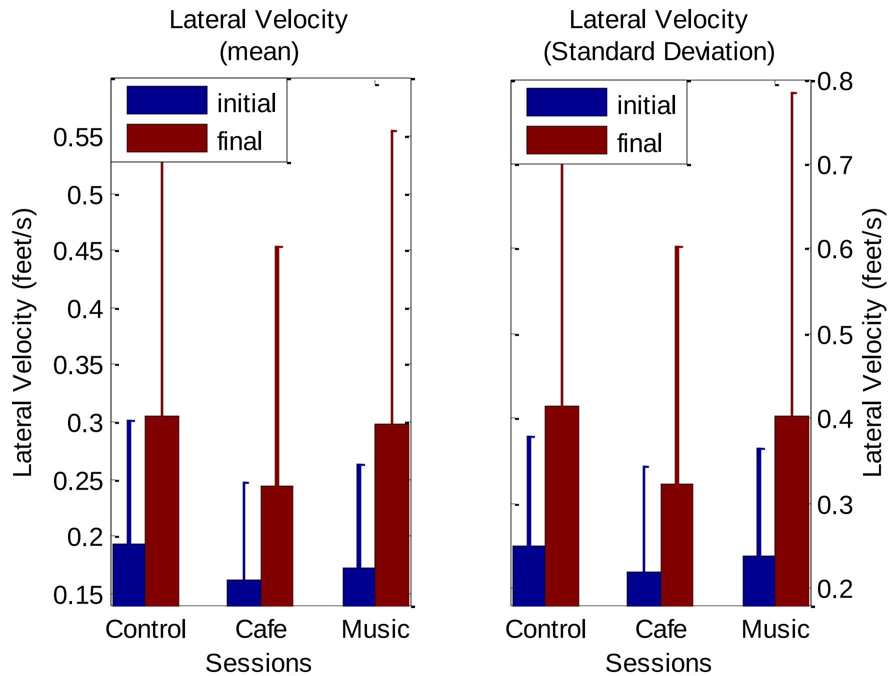


Figure 26 means and standard deviations of LV at beginnings and ends of three sessions

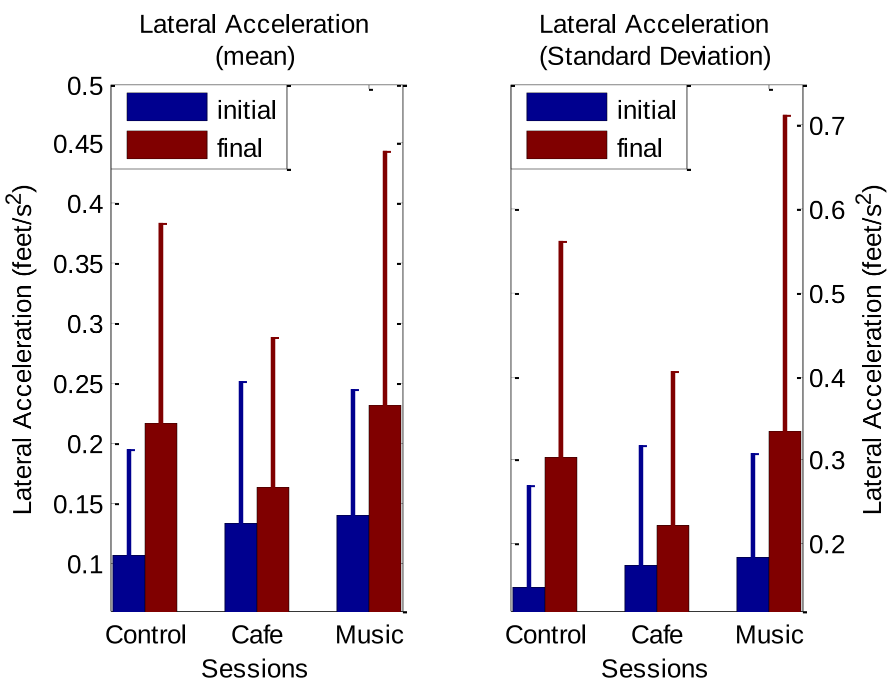


Figure 27 means and standard deviations of LA at beginnings and ends of three sessions

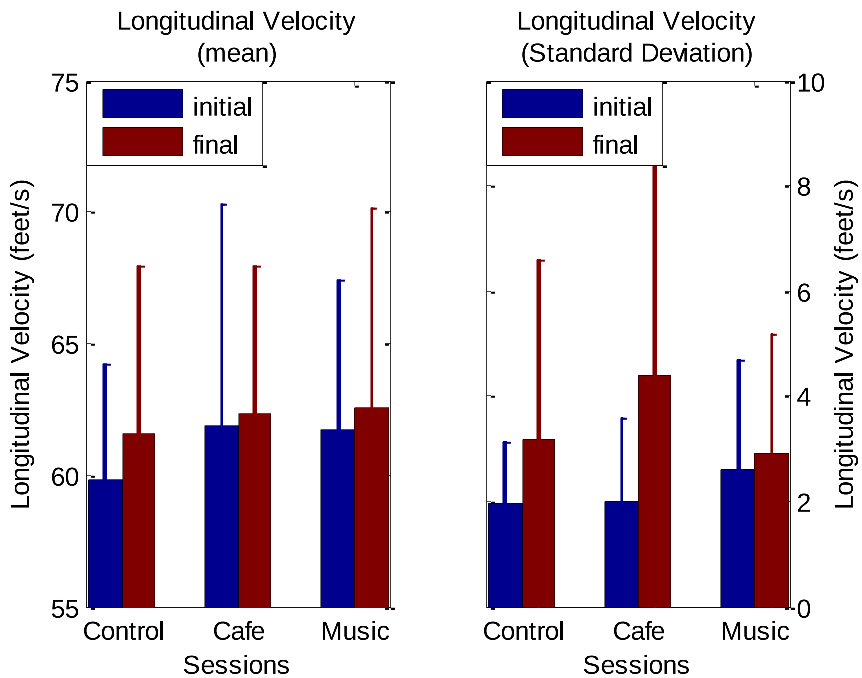


Figure 28 means and standard deviations of VE at beginnings and ends of three sessions

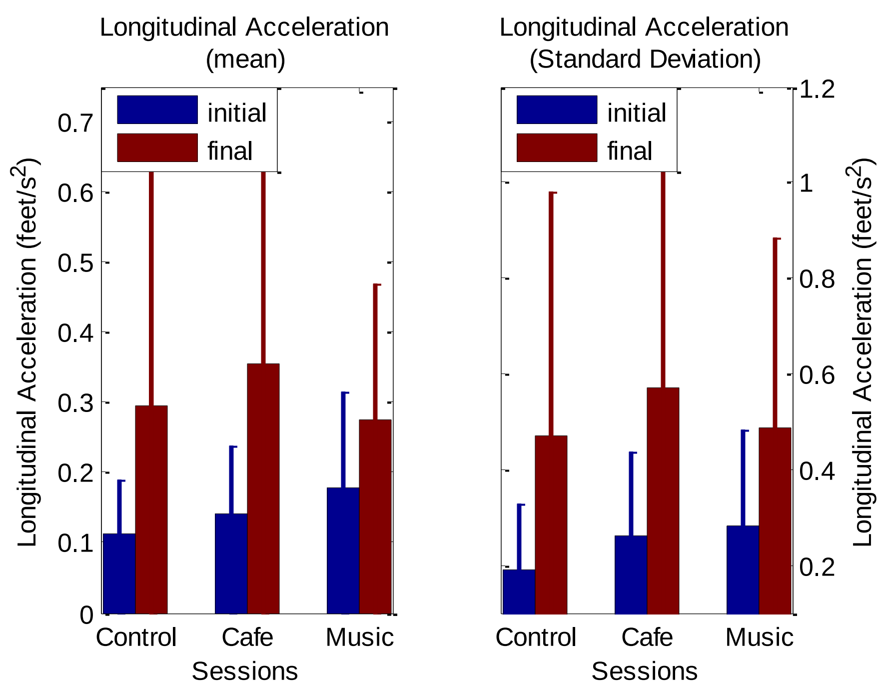


Figure 29 means and standard deviations of AC at beginnings and ends of three sessions

6.3 EEG

6.3.1 EEG activities

In section 4.2.6, **Error! Reference source not found.** has been introduced to obtain the averaged EEG. An averaged EEG was plotted for the 1st subject, at the 1st Lane Keeping Task in the control session, as shown in Figure 30 (A). This section of wave was denoted as ${}_1^1fp^1(t)$, where $t = 0{\sim}300\ seconds$. The wave was decomposed into four frequency components of EEG and noises. The four frequency components were obtained from this recording, which were delta (δ, 0.5~4 Hz), theta (θ, 4~8 Hz), alpha (α, 8~13 Hz), and beta (β, 13~20 Hz) waves. Delta and theta waves are relatively low frequency components of an EEG, compared to alpha and beta waves. Delta components are the lowest of the four and usually associated with deep sleep or certain brain diseases. Theta waves are also low frequency components and are often observed in a normal person who is involving a cognitive task or in a person who is in degenerative brain states. Alpha and beta waves are relatively faster EEG components. Alpha waves are observed in a person who is in onset of sleep, often with eyes closed; but when the person falling asleep, alpha waves disappear. Beta components represent an active brain state, for example, experiencing an external stimulus [76, 104]. The four components were also plotted in Figure 30 (B), (C), (D), and (E) respectively. The four components were denoted as ${}_1^1\delta^1(t)$, ${}_1^1\theta^1(t)$, ${}_1^1\alpha^1(t)$, and ${}_1^1\beta^1(t)$ respectively, again, $t = 0{\sim}300\ seconds$.

Each section of averaged EEG was divided into 150 2-second subsections and denoted as ${}_1^1fp_n{}^1(t)$, where $n = 1{\sim}150$. Each subsection contained averaged EEG of 2 seconds, therefore, the 1st subsection was represented as ${}^{1}_{1}fp_1{}^{1}(t) = {}^{1}_{1}fp^{1}(t)|_{t=0\sim2}$, the 2nd was ${}^{1}_{1}fp_2{}^{1}(t) = {}^{1}_{1}fp^{1}(t)|_{t=2\sim4}$, and so on.

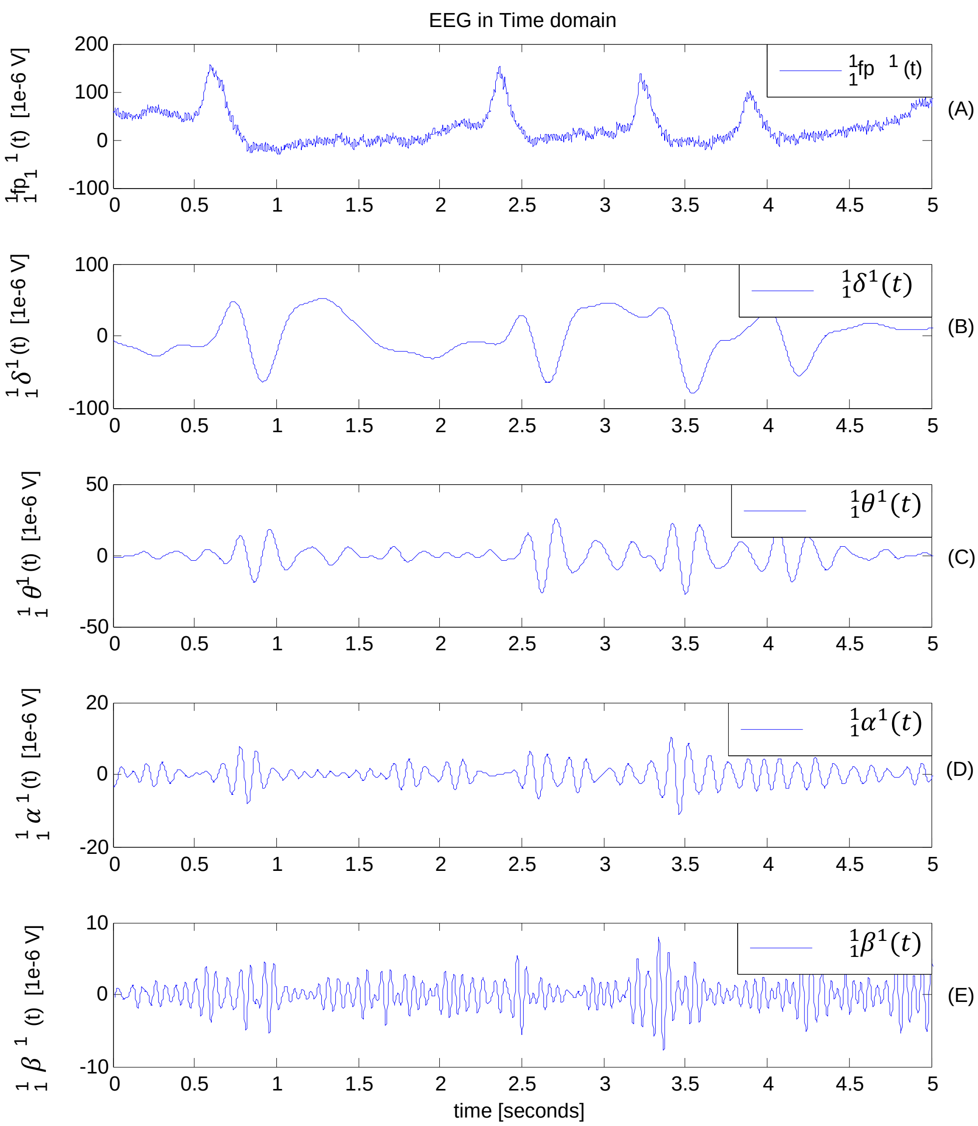


Figure 30 EEG signal in time domain, (only plotted the waves in the first 5 seconds)

Each subsection was subjected to a Fast Fourier Transform (FFT). The FFT analysis generated spectral magnitude which was denoted as ${}^{s}_{T}FP^{m}(f)$, with the same unit of ${}^{s}_{T}fp^{m}(t)$. This relationship was mathematically expressed by Equation 6-1.

$$ {}^{s}_{T}FT_{n}{}^{m}(f) = \int_{-\infty}^{\infty} {}^{s}_{T}fp_{n}{}^{m}(t)\, e^{-jft} dt \; = \; FFT(\, {}^{s}_{T}fp_{n}{}^{m}(t)) \qquad \text{Equation 6-1} $$

where:

$FFT = Fast\ Fourier\ Transform\ function\ in\ MATLAB$

$f \quad = frequency$

A typical subsection of averaged EEG was plotted in Figure 31 (A), and its FFT was plotted in Figure 31 (B). It showed that the Direct Current (DC) component of the averaged EEG was 48.01 μv, when $f = 0$. It also showed a peak at $f = 60$, which indicated the noise generated by surrounding 60 Hz electromagnetic sources. The relevant frequency bands (δ, θ, α, and β) in frequency domain were also obtained, as shown in Figure 31 (C). These calculations were handled by an algorithm developed in MATLAB environment.

Delta components. The area under the curve ${}^{s}_{T}FT_{n}{}^{m}(f)$ between 0.5 and 4 *Hz* represented the power spectrum of the δ component, and denoted as ${}^{s}_{T}A\delta_{\mathrm{n}}{}^{m}$, which can be calculated using Equation 6-2 (A). The power spectrum, ${}^{s}_{T}A\delta_{\mathrm{n}}{}^{m}$, reflected the current delta activity of the m^{th} subject at the n^{th} subsection (within 2 seconds) during the T^{th} Lane Keeping Task in the s^{th} driving session (1st = control session, 2nd =caffeine session,

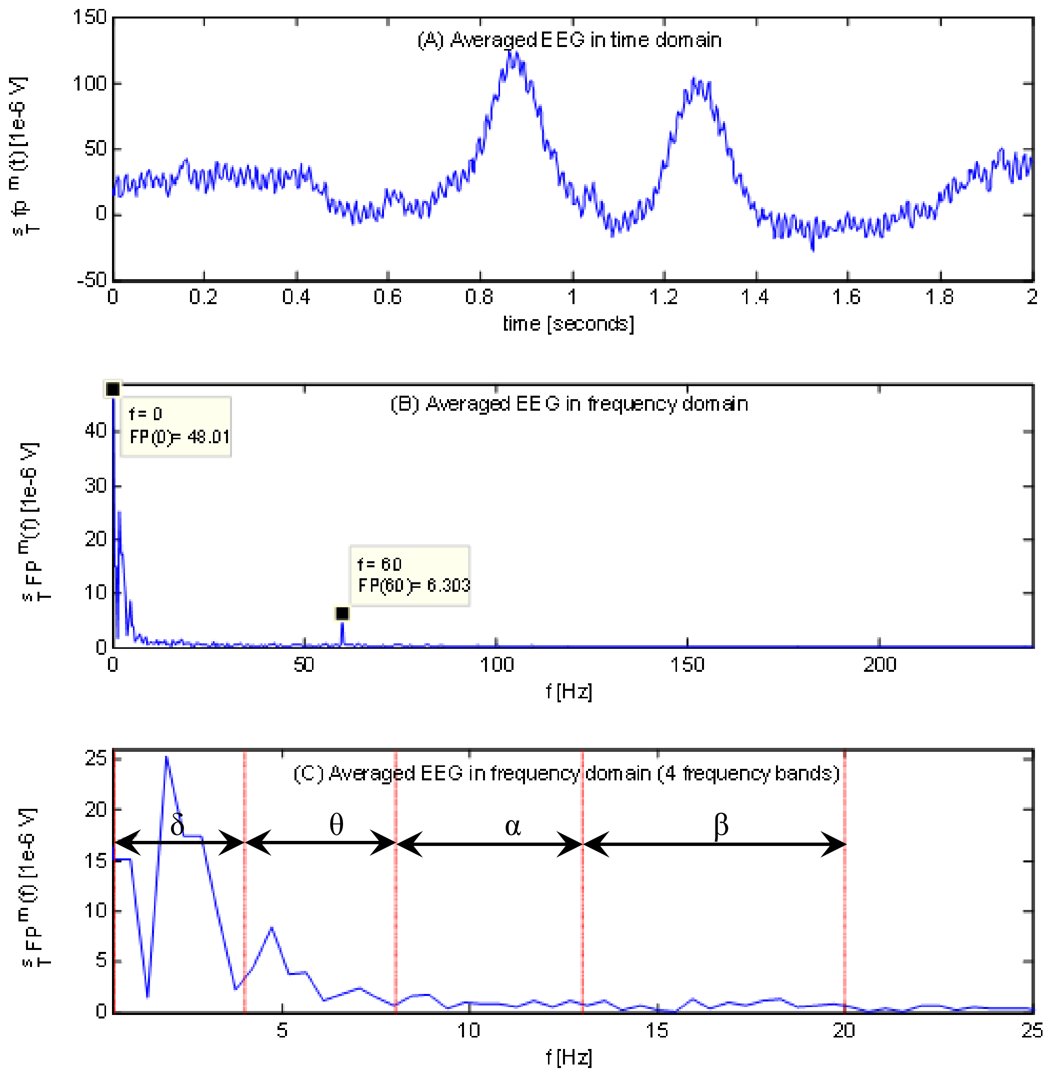


Figure 31 FFT analysis of an EEG signal subsection (2 seconds)

and 3rd = music session). The average delta activity of this m^{th} subject during the s^{th} Lane Keeping Task (5 minutes) in the s^{th} driving session was denoted as ${}^{s}_{T}A\delta^{m}$, and was calculated using Equation 6-3 (A). Therefore, for each of three 2-hour driving sessions, an individual subject had the delta activity estimated 9 times: ${}^{s}_{1}A\delta^{m} \sim {}^{s}_{9}A\delta^{m}$. For example, the delta activities of an individual subject in the control section, ${}^{1}_{1}A\delta^{m} \sim {}^{1}_{9}A\delta^{m}$, were plotted as red circles in Figure 32 (A). The delta activities of this subject in the caffeine and music sessions were also plotted as blue stars and black triangles in Figure 32 (A).

$$ {}_{T}^{s}A\delta_{\mathrm{n}}{}^{m} = \int_{f=0.5}^{4} {}_{T}^{s}FT_{n}{}^{m}(f)\,df \qquad \text{Equation 6-2 (A)}$$

$$ {}_{T}^{s}A\delta^{m} = \frac{1}{150}\sum_{n=1}^{150} {}_{T}^{s}A\delta_{\mathrm{n}}{}^{m} \qquad \text{Equation 6-3 (A)}$$

n = 1~150 , the number of 2-second subsection of EEG in T^{th} Lane Keeping Task

The mean of delta activities during each Lane Keeping Task was calculated for all twenty subjects using Equation 6-4 (A), and denoted as $\overline{{}_{T}^{s}A\delta}$. The mean of delta activities of the group was plotted against driving time in Figure 32 (B): red circles for the control session, blue stars for the caffeine session, and black triangles for the music session. Although some scatter was shown in the plots, a trend of increase in delta activity was observed in each driving session.

The delta activities at the beginnings of the three sessions were similarly low: 96.2 for control session, 94.4 for caffeine session, and 98 for music session.

$$ \overline{{}_{T}^{s}A\delta} = \frac{1}{20}\sum_{m=1}^{20} {}_{T}^{s}A\delta^{m} \qquad \text{Equation 6-4 (A)}$$

$$ {}_{T}^{s}\Delta A\delta^{m} = {}_{9}^{s}A\delta^{m} - {}_{1}^{s}A\delta^{m} \qquad \text{Equation 6-5 (A)}$$

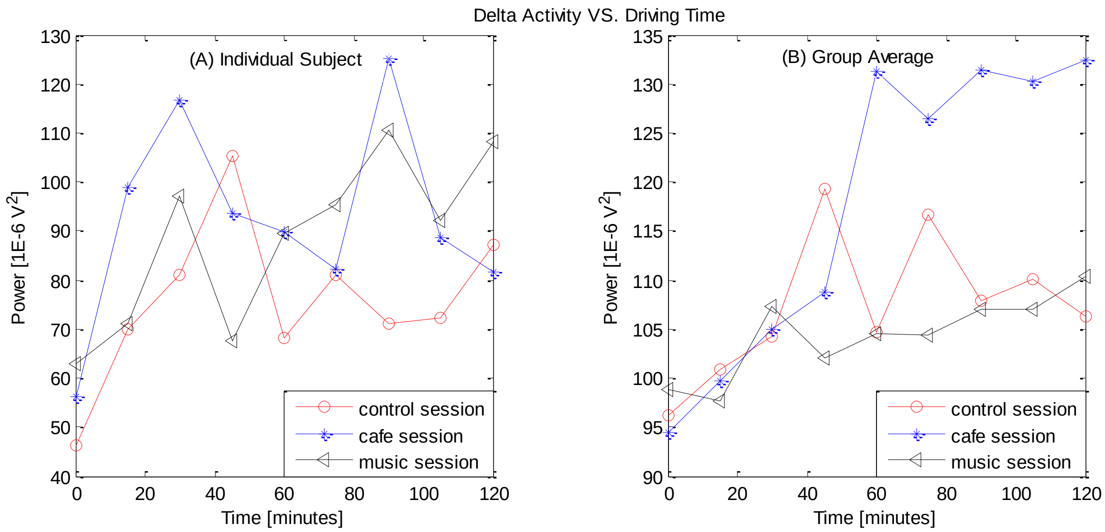
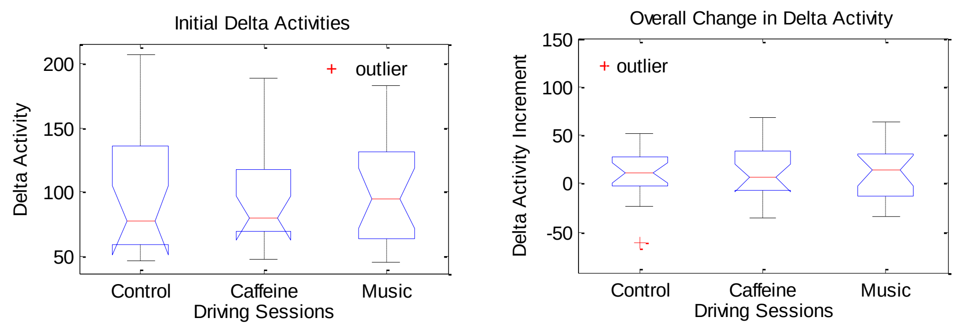


Figure 32 Delta Activity VS. time

Since the subjects were required to start each session at the same time of the day and with the similar states, small variations were expected. One-way ANOVA was used to examine variations in the initial delta activities of all 20 subjects and no significant differences were observed [F(2,57,59)=0.06, p=0.9455], as shown in Figure 33 (A). Multi-comparison was performed using the Tukey test. The result showed that there was no significant difference between any two of the three driving sessions at the beginning. This indicated that each driver started all the three sessions at the same fatigue levels. This was also shown in Figure 32 (A) and (B). Although, each driver started the three sessions with similar delta activities, the means of the group were different at the ends of three sessions, as shown in Figure 32: the mean delta activities at the end of caffeine session was higher than control and music sessions.



(A) (B)

Figure 33 Variations in Delta activity

A series of paired student *t*-tests were performed to check whether changes in delta activities were significant after 120-minute driving sessions. The results showed that significant changes were not found in any of three sessions [p=0.1007, *t* = -1.72, CI=(-22.1, 2.12)] for control session; p=0.1741, *t* = -1.41, CI=(-94.3, 18.31) for caffeine session; p=0.0649, *t* = -1.95, CI=(-23.8, 0.78) for music session]. The increments of delta activities after completing each driving session, ${}^{s}_{T}\Delta A\delta^{m}$, were calculated using Equation 6-5 (A). Group average increments of delta activities were (1) largest for caffeine session, 37.98, (2) medium for music session, 11.50, and (3) smallest for control session, 9.99. Further analysis, using one-way ANOVA, revealed that the increment was not significantly different between any two of the three driving sessions [F(2,57,59)=0.94, p=0.3968]. The results were also shown in Figure 33(B).

In general, delta activities were relatively low but similar when each driver started the driving sessions. After each of the driving sessions, delta activities shown a trend of increase, but no evidence indicated the increase was significant. The group average showed that the overall increments in delta activities were smallest in control session, largest in caffeine session, and medium in music session. However, the increments were not significantly different between any two of three driving sessions.

It was also worth to notice that delta activities increased during the early stage of control session and reached the peak value at 40 minutes; then a trend of decrease were shown in the rest of the control session. A similar pattern of changes in delta activity was also observed by other researchers [77].

However, changes in delta activities showed different patterns in caffeine and music session. In the caffeine session, delta activities rapidly increased in the first half session and reached a local peak value, then gradually stabilized toward the end of driving session. In the music session, delta activities increased in the first 30 minutes, similarly as in control and caffeine session. After that delta activities decreased for about 15 minutes, then continuously increased towards the end of the driving session.

Theta components Similarly, the power spectrum was calculated to reflect the current theta activity of the m^{th} subject at the n^{th} subsection (within 2 seconds) during the T^{th} Lane Keeping Task in the sth driving session, and was denoted as ${}^{\mathrm{s}}_{\mathrm{T}}\mathrm{A\theta_n}^{\mathrm{m}}$, which can be calculated by using Equation 6-2 (B). The average theta activity of the five-minute Lane Keeping Task, ${}^{\mathrm{s}}_{\mathrm{T}}\mathrm{A\theta}^{\mathrm{m}}$, was calculated using Equation 6-3 (B) for individual subjects.

$$ {}^{s}_{T}A\theta_{\mathrm{n}}{}^{m} = \int_{f=4}^{8} {}^{s}_{T}FT_n{}^{m}(f)\, df \qquad \text{Equation 6-2 (B)} $$

$$ {}_{T}^{s}A\theta^{m} = \frac{1}{150}\sum_{n=1}^{150} {}_{T}^{s}A\theta_{n}{}^{m} \quad \text{Equation 6-3 (B)} $$

$$ \overline{{}_{T}^{s}A\theta} = \frac{1}{20}\sum_{m=1}^{20} {}_{T}^{s}A\theta^{m} \quad \text{Equation 6-4 (B)} $$

$$ {}_{T}^{s}\Delta A\theta^{m} = {}_{9}^{s}A\delta^{m} - {}_{1}^{s}A\theta^{m} \quad \text{Equation 6-5 (B)} $$

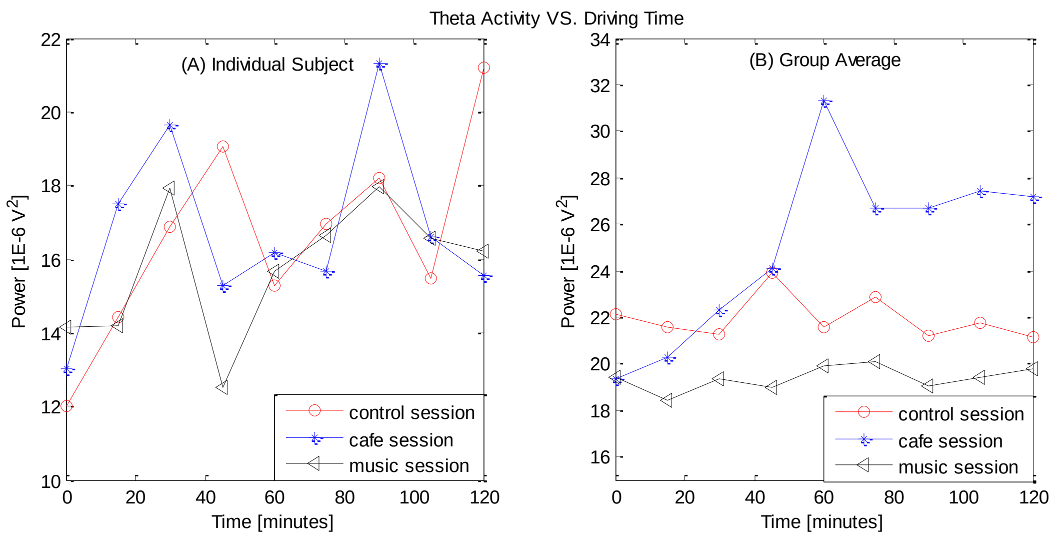
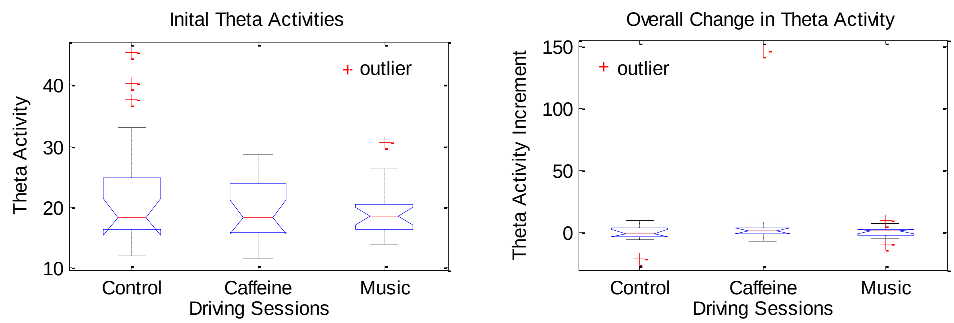


Figure 34 Theta Activity VS. Time

The theta activities of an individual subject were plotted against driving time in Figure 34 (A): red circles for control session, blue stars for caffeine session, and black triangles for music sessions. The mean of theta activities were calculated using Equation 6-4 (B), and plotted in Figure 34 (B). The results showed that the group mean of the theta activity only increased after finishing the caffeine session. A one way ANOVA was used to examine variations in the initial theta activities at the beginning of the three sessions of all 20 subjects. The results showed that the theta activities were similar (22.1

for control session, 19.4 for caffeine session, and 19.4 for music session) and no significant difference were found [F(2,57,59)=1.08, p=0.3457], as shown in Figure 35(A). Multi-comparison was performed using Tukey test, indicating no significant difference between any two of the three driving sessions at the beginnings.



(A) (B)

Figure 35 Variations in Theta Activity

A series of paired student *t*-test were performed to check whether changes in theta activities were significant after each 120-minute driving session. The results showed that the theta activity were (1) not significantly changed after the control session [p=0.5265, *t* = 0.65, CI=(-2.235, 4.2273)], (2) not significantly changed after the caffeine session [p=0.3028, *t* = -1.06, CI=(-23.3058, 7.6446)], and (3) not significantly changed after the music session [p=0.7107, *t* = -0.38, CI=(-2.3758, 1.6515)]. The increments of theta activities, ${}_{T}^{s}\Delta A\theta^{m}$, were calculated using Equation 6-5 (B). Group average increment of theta activities were decreased after control session (-0.9961), increased after caffeine session (7.8306) and music session (3.622). However, one-way ANOVA analysis showed that the increment was not significantly different between any two of the three driving sessions [F(2,57,59)=1.17, p=0.318]. The results were also shown in Figure 35(B).

In general, theta activities were similar when each subject started the three driving sessions. After the caffeine session, the theta activity was increased, but the change was not significant. Variations of the theta activities were not noticeable after control and music sessions.

Alpha component. The power spectrum of the alpha activity calculated the area under the curve between 8Hz and 13Hz shown in Figure 31, using Equation 6-2 (C). Then the average alpha activity for the five-minute Lane Keeping Task, ${}^{s}_{T}A\alpha^{m}$, was calculated using Equation 6-3 (C) for individual subjects. The alpha activities of an individual subject were plotted against time in Figure 36 (A).

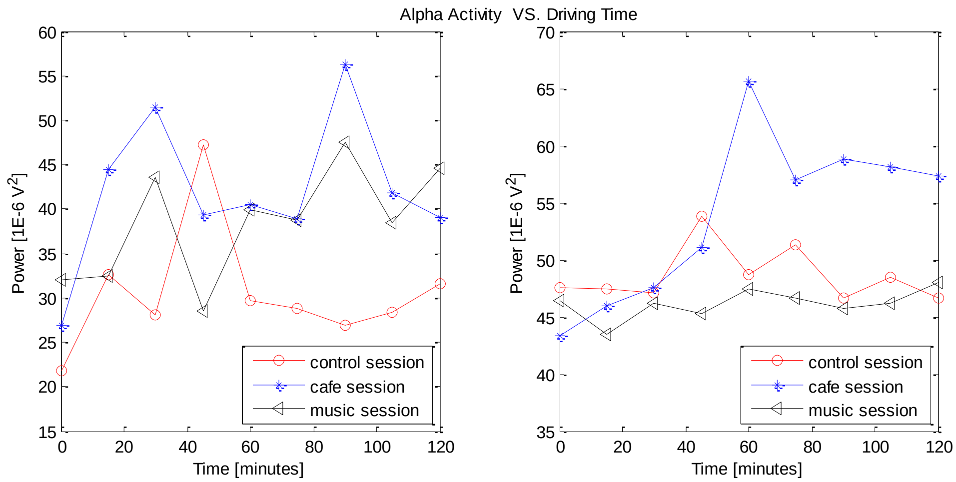
$$ {}^{s}_{T}A\alpha_{n}{}^{m} = \int_{f=8}^{13} {}^{s}_{T}FT_{n}{}^{m}(f)\, df \qquad \text{Equation 6-2 (C)} $$

$$ {}^{s}_{T}A\alpha^{m} = \frac{1}{150} \sum_{n=1}^{150} {}^{s}_{T}A\alpha_{n}{}^{m} \qquad \text{Equation 6-3 (C)} $$

$$ \overline{{}^{s}_{T}A\alpha} = \frac{1}{20} \sum_{m=1}^{20} {}^{s}_{T}A\alpha^{m} \qquad \text{Equation 6-4 (C)} $$

$$ {}^{s}_{T}\Delta A\alpha^{m} = {}^{s}_{9}A\delta^{m} - {}^{s}_{1}A\alpha^{m} \qquad \text{Equation 6-5 (C)} $$

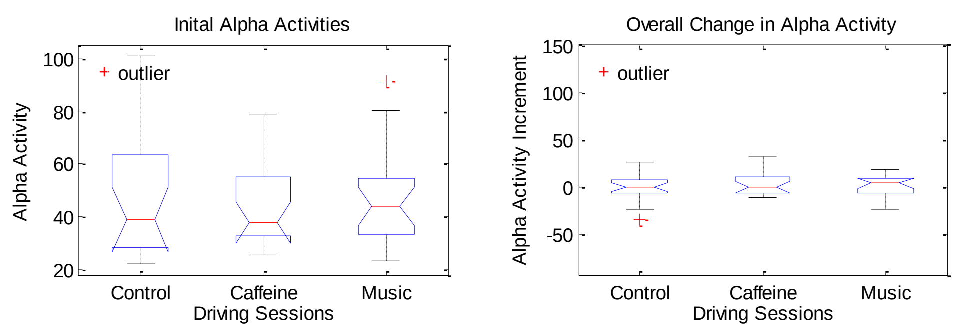
The group mean of alpha activities for the 20 subjects, $\overline{{}^{s}_{T}A\alpha}$, were calculated using Equation 6-4 (C) and plotted in Figure 36(B). The plot showed that the group mean of the alpha activity increased after the caffeine session only. A one-way ANOVA indicated



(A) (B)

Figure 36 Alpha Activity VS. time

that the alpha activities were similar at the beginnings of the three driving sessions (47.5 for the control session, 43.4 for the caffeine session, and 46.5 for the music session), and not significantly different [F(2,57,59)=0.2426, p=0.7854], as shown in Figure 37(A). Multi-comparison was also performed, indicating no significant difference between any two of the three driving sessions at the beginnings; this result was also shown in Figure 37(A).



(A) (B)

Figure 37 Variation in Alpha Activity

The results of a series of paired student *t*-tests showed that changes in the alpha activity was (1) not significant [p=0.7721, t = 0.29, CI=(-5.2825, 7.0076)], (2) not significant [p=0.2339, t = -1.23, CI=(-37.6267,9.7784)], and (3) not significant [p=0.5674, t = -0.58, CI=(-7.2825,4.1133)]. The increments of alpha activities, ${}_{T}^{s}\Delta A\alpha^{m}$, were calculated using Equation 6-5 (C). Group average increment of alpha activities were decreased after the control session (-0.8625), increased after caffeine session (13.9242), and increased after music session (1.5846). However, one-way ANOVA analysis showed that the increment was not significantly different between any two of the three driving sessions [F(2,57,59)=1.3062 , p=0.2788]. The results were also shown in Figure 37(B).

In general, alpha activities were similar at the beginnings of the three driving sessions. After the caffeine session, the alpha activity was increased, but the change was not significant. Variations of the alpha activities were not noticeable after control and music sessions.

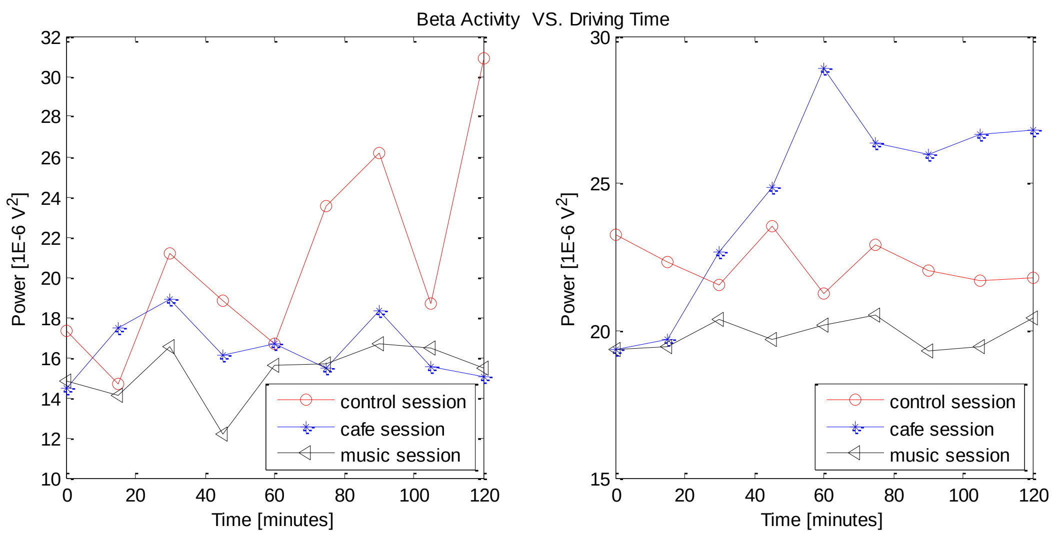
Beta components. The power spectrum of the beta activity calculated the area under the curve between 13Hz and 20Hz shown in Figure 31, using Equation 6-2 (D). Then the average beta activity for the five-minute Lane Keeping Task, ${}_{\mathrm{T}}^{\mathrm{s}}\mathrm{A}\beta^{\mathrm{m}}$, was calculated using Equation 6-3 (D) for individual subjects. The beta activities of an individual subject were plotted against time in Figure 38 (A).

$${}_{T}^{s}A\beta_{\mathrm{n}}{}^{m} = \int_{f=13}^{20} {}_{T}^{s}FT_{n}{}^{m}(f)\, df$$ Equation 6-2 (D)

$${}_{\mathrm{T}}^{\mathrm{s}}\mathrm{A}\beta^{\mathrm{m}} = \frac{1}{150}\sum_{\mathrm{n}=1}^{150} {}_{\mathrm{T}}^{\mathrm{s}}\mathrm{A}\beta_{\mathrm{n}}{}^{\mathrm{m}}$$ Equation 6-3 (D)

$$\overline{{}_{T}^{s}A\beta} = \frac{1}{20}\sum_{m=1}^{20} {}_{T}^{s}\mathrm{A}\beta^{m}$$ Equation 6-4 (D)

$${}_{T}^{s}\Delta A\beta^{m} = {}_{9}^{s}A\delta^{m} - {}_{1}^{s}A\beta^{m}$$ Equation 6-5 (D)

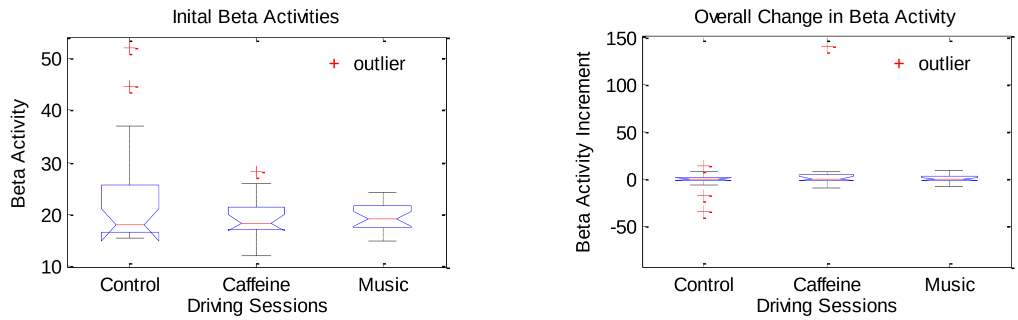


(A) (B)

Figure 38 Beta Activity VS. time

The group mean of beta activities, $\overline{{}_{T}^{S}A\beta}$, were calculated using Equation 6-4 (D) and plotted in Figure 38 (A). The plot showed that the average beta activity increased after the caffeine session only. A one-way ANOVA indicated that the beta activities were similar at the beginnings of three driving sessions (23.2481 for the control session, 19.3444 for the caffeine session, and 19.3396 for the music session), and not significantly different [F(2,57,59)=2.2571, p=0.1139], as shown in Figure 39(A). Multi-comparison was performed, indicating that no significant difference between any two of the three driving sessions at the beginnings.

The results of a series of paired student *t*-tests showed that changes in the beta activity was (1) not significant after control session [p=0.5073, t = 0.68, CI=(-3.0571, 5.9722)], (2) not significant after the caffeine session [p=0.3016, t = -1.06 CI=(-22.2024, 7.2565)], and (3) not



(A) (B)

Figure 39 Variation in Beta Activity

significant after music session [p=0.2522, t = -1.18, CI=(-3.0287, 0.8436)]. The increments of beta activities, ${}^{S}_{T}\Delta A\beta^{m}$, were calculated using Equation 6-5 (D). Group average increment of beta activities were decreased after the control session (-1.4576), increased after caffeine session (7.4730), and increased after music session (1.0926). However, one-way ANOVA analysis showed that the increment was not significantly different between any two of the three driving sessions [F(2,57,59)=1.1535 , p=0.3228]. The results were also shown in Figure 39(B).

In general, beta activities were similar at the beginning of the three driving sessions. After the caffeine session, the beta activity was increased, but the change was not significant. Variations of the beta activity were not noticeable after the control and music session.

6.3.2 Ratios of slow wave to fast wave

In recent research, four ratios of slow wave to fast wave have been suggested as fatigue indicators [77]. These four ratios were calculated based on the power spectrum of delta, theta, alpha, and beta components given by Equation 6-2 (A) ~ (D). It was reported that all these ratios showed increase over time and could be implicated for detecting fatigue.

R1 – theta/beta. The first indicator was denoted as ${}_{T}^{s}R1_{\mathrm{n}}{}^{m}$ and obtained using Equation 6-2 (E), representing the ratio of the current theta spectrum over beta spectrum. The value reflected the current status of the *m*th subject at the n^{th} subsection (within 2 seconds) during the T^{th} Lane Keeping Task in the s^{th} driving session (1^{st} = control session, 2^{nd} =caffeine session, and 3^{rd} = music session). The average fatigue levels during the s^{th} Lane Keeping Task (5 minutes) in the s^{th} driving session was denoted as ${}_{\mathrm{T}}^{\mathrm{s}}R1^{\mathrm{m}}$ and calculated using Equation 6-3 (E). Therefore, nine estimations, ${}_{1}^{\mathrm{s}}R1^{\mathrm{m}}$~ ${}_{9}^{\mathrm{s}}R1^{\mathrm{m}}$, were obtained during each driving session for an individual subject. For example, ${}_{1}^{1}R1^{\mathrm{m}}$~ ${}_{9}^{1}R1^{\mathrm{m}}$ of an individual subject in the control session were plotted as red circles in Figure 40 (A). The estimations in the caffeine and music sessions were also plotted as blue starts and black triangles.

The mean of R1 during each Lane Keeping Task was calculated for all twenty subjects using Equation 6-4 (E), and denoted as $\overline{{}_{T}^{s}R1}$. The group means of R1 were plotted in Figure 40 (B): red circles for the control session, blue starts for the caffeine session, and black triangles for the music session. From the plot, no absolute change was observed in each driving session.

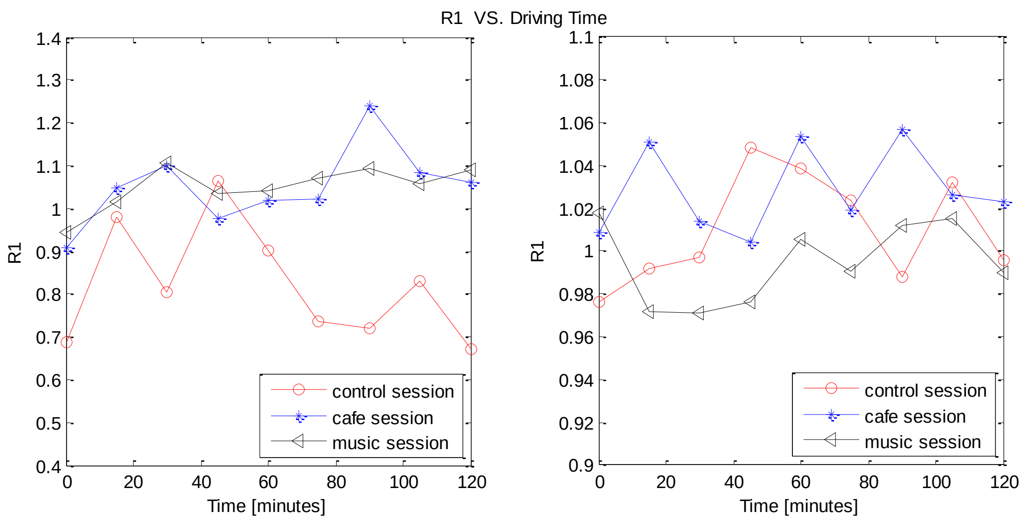
$${}_{T}^{s}R1_{\mathrm{n}}{}^{m} = {}_{T}^{s}A\theta_{\mathrm{n}}{}^{m} \Big/ {}_{T}^{s}A\beta_{\mathrm{n}}{}^{m} \qquad \text{Equation 6-2 (E)}$$

$$ {}_{T}^{S}R1^{m} = \frac{1}{150}\sum_{n=1}^{150} {}_{T}^{S}R1_{n}^{\;m} $$ Equation 6-3 (E)

$$ \overline{{}_{T}^{S}R1} = \frac{1}{20}\sum_{m=1}^{20} {}_{T}^{S}R1^{m} $$ Equation 6-4 (E)

Equation 6-5 (E)

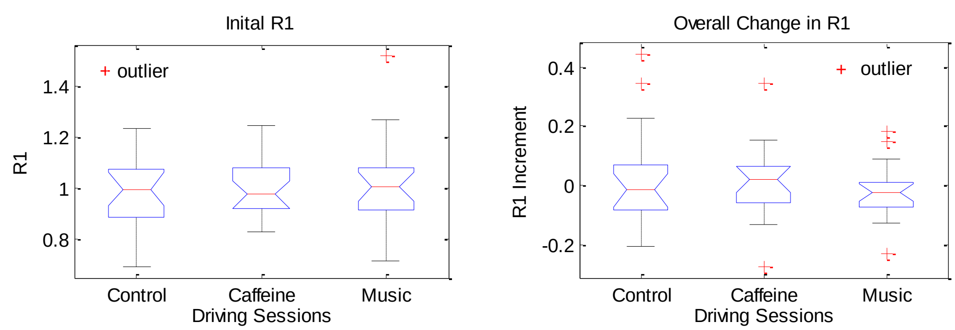
$$ {}_{T}^{S}\Delta R1^{m} = {}_{9}^{S}R1^{m} - {}_{1}^{S}R1^{m} $$



(A) (B)

Figure 40 R1 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.

The group means of R1 were 0.976 for the control session, 1.0091 for the caffeine session, and 1.0176 for the music sessions. A one-way ANOVA was performed and the result showed that R1 at the beginnings of the three driving session were not significantly different [F(2,57,59)=0.4464, p=0.6422], the result was also shown in Figure 41(A). Multi-comparison was performed using the Tukey test, showing that there was no significant difference of R1 between any two of the three driving sessions at the beginnings. A series of paired student *t*-tests were performed to examine whether R1 was significantly changed after each 120-minute driving session. The results showed no significant changes in any of three sessions [p=0.5977, t = -0.54, CI=(-0.0961, 0.0569) for the control session; p=0.6341, t = -0.48, CI=(-0.0733, 0.0458) for the caffeine session; p=0.2481, t = 1.19, CI=(-0.0207, 0.0756) for the music session]. The increments of R1 after completing each driving session, ${}^{s}_{T}\Delta R1^{m}$, were calculated using Equation 6-5 (E). Group average increments of R1 were 0.0196 for the control session, 0.0138 for the caffeine session, and -0.0274 for the music session. Further analysis, using a one-Way ANOVA, revealed that the increment was not significantly different among the three driving sessions [F(2, 57,59)=0.7371, p=0.4830]. Performance of multi-comparison using the Tukey test revealed that there was no significant difference of the increment in R1 between any two of the three driving sessions. The results were also shown in Figure 41(B).



(A)　　(B)

Figure 41 R1 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.

In summary, the ratio of the theta spectrum over beta spectrum, R1, were initially similar and showed no significant difference at the beginnings of the three driving sessions. After each 120-minute driving session, R1 was not significantly changed. The increments (or overall changes) of R1 after the driving session were not significantly different among the three driving sessions.

R2 – alpha/beta. The second indicator was denoted as, ${}^{s}_{T}R2_{\mathrm{n}}{}^{m}$, and calculated using Equation 6-2 (F), representing the ratio of the current alpha spectrum over beta spectrum. The value reflected the current status of the subject. The average status during the Lane Keeping Task was denoted as ${}^{s}_{\mathrm{T}}R2^{\mathrm{m}}$ and calculated using Equation 6-3 (F). The average R2 of an individual subject were plotted in Figure 42(A): red circles for the control session, blue stars for the caffeine session, and black triangles for the music session. The group means of R2 during each Lane Keeping Task, $\overline{{}^{s}_{T}R2}$, were calculated using Equation 6-4 (F) and were plotted in Figure 42 (B). The initial group means of R2 were 2.108 for the control session, 2.2982 for the caffeine session, and 2.4689 for the music session. A one-way ANOVA analysis suggested that R2 were not significantly different at the beginnings of the three driving sessions. Multi-comparison was performed using the Tukey test, showing that there was no significant difference in R1 between any two of the three sessions at the beginning. This was also shown in Figure 43(A).

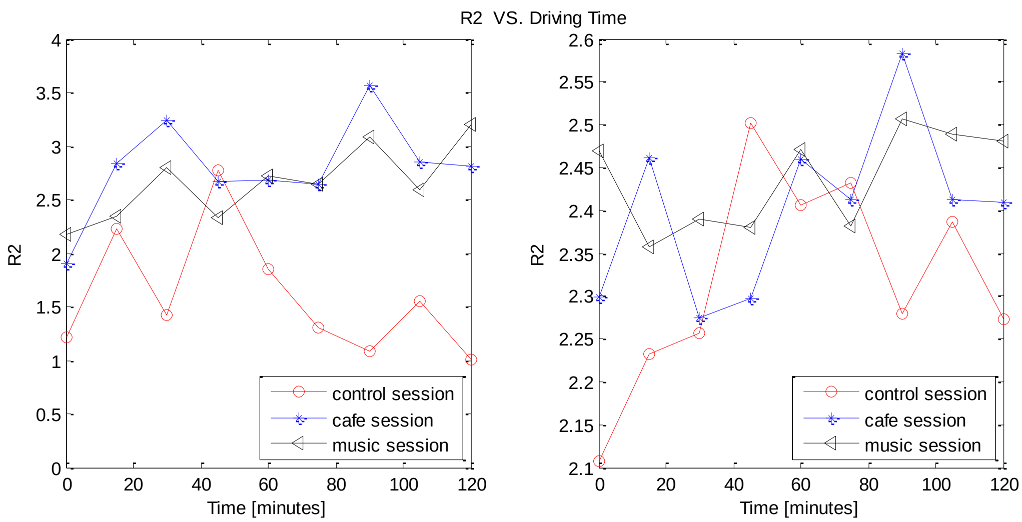
$$ {}^{s}_{T}R2_{\mathrm{n}}{}^{m} = {}^{s}_{T}A\alpha_{\mathrm{n}}{}^{m} \Big/ {}^{s}_{T}A\beta_{\mathrm{n}}{}^{m} \qquad \text{Equation 6-2 (F)} $$

$$ {}^{s}_{\mathrm{T}}R2^{\mathrm{m}} = \frac{1}{150}\sum_{\mathrm{n}=1}^{150} {}^{s}_{\mathrm{T}}\mathrm{R2}_{\mathrm{n}}{}^{\mathrm{m}} \qquad \text{Equation 6-3 (F)} $$

$$ \overline{{}^{s}_{T}R2} = \frac{1}{20}\sum_{m=1}^{20} {}^{s}_{T}R2^{m} \qquad \text{Equation 6-4 (F)} $$

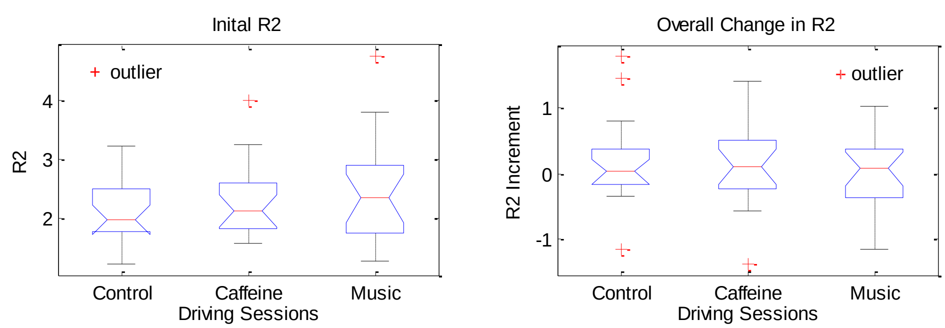
$$ {}^{s}_{T}\Delta R2^{m} = {}^{s}_{9}R2^{m} - {}^{s}_{1}R2^{m} \qquad \text{Equation 6-5 (F)} $$

A series of paired student t-tests were performed to examine whether R2 was significantly changed after each 120-minute driving session. The results showed no significant changes in any of three sessions [p=0.2626, t = -1.15, CI=(-0.4651, 0.1344) after the control session; p=0.418, t = -0.83, CI=(-0.3945, 0.1709) after the caffeine session; p=0.9187, t = -0.10, CI=(-0.2525, 0.2288) after the music session]. The increments of R2 after completing each driving session, ${}^{s}_{T}\Delta R2^{m}$, were calculated using Equation 6-5 (F). Group average increments of R2 were 0.1653 for the control session, 0.1118 for the caffeine session, and 0.0119 for the music session.



(A) (B)

Figure 42 R2 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.



(A) (B)

Figure 43 R2 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.

Further analysis using a one-way ANOVA revealed that the increment of R2 was not significantly different among the three driving sessions [F(92,57,59)=0.3502, p=0.7061]. Performance of multi-comparison using the Tukey test revealed that there was no significant difference in R1 increments between any two of the three driving sessions. The results were also shown in Figure 43(B).

In summary, the ratio of the alpha spectrum over beta spectrum, R2, were initially similar and showed no significant difference at the beginnings of the three driving sessions. After each 120-minute driving session, R2 was not significantly changed. The increments (overall changes) of R2 after the driving session were not significantly different among the three driving sessions.

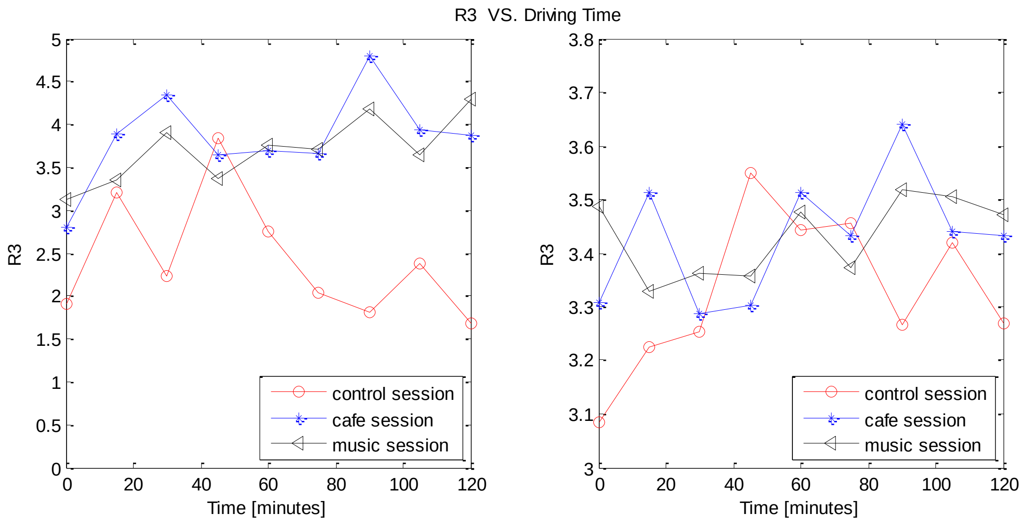
R3 – (theta + alpha)/beta. The third indicator was denoted as ${}_{T}^{s}R3_{\mathrm{n}}{}^{m}$, and calculated using Equation 6-2 (G), representing the ratio of the summation of theta and alpha spectrum over beta spectrum. The value reflected the current status of the subject. The average status during the Lane Keeping Task was reflected by ${}_{\mathrm{T}}^{s}R3^{\mathrm{m}}$, which was calculated using Equation 6-3 (G). The average R3 of an individual subject were plotted in Figure 44(A): red circles for the control session, blue starts for the caffeine session, and black triangles for the music session. The group means of R3 during each Lane Keeping Task, $\overline{{}_{T}^{s}R3}$, were calculated using Equation 6-4 (G) and plotted in Figure 44(B).

$$ {}_{T}^{s}R3_{\mathrm{n}}{}^{m} = \left({}_{T}^{s}A\alpha_{\mathrm{n}}{}^{m} + {}_{T}^{s}A\theta_{\mathrm{n}}{}^{m}\right) \Big/ {}_{T}^{s}A\beta_{\mathrm{n}}{}^{m} \qquad \text{Equation 6-2 (G)} $$

$$ {}_{\mathrm{T}}^{s}R3^{\mathrm{m}} = \frac{1}{150}\sum_{\mathrm{n}=1}^{150} {}_{\mathrm{T}}^{s}R3_{\mathrm{n}}{}^{\mathrm{m}} \qquad \text{Equation 6-3 (G)} $$

$$\overline{{}_{T}^{s}R3} = \frac{1}{20}\sum_{m=1}^{20} {}_{T}^{s}R3^{m}$$ Equation 6-4 (G)

$${}_{T}^{s}\Delta R3^{m} = {}_{9}^{s}R3^{m} - {}_{1}^{s}R3^{m}$$ Equation 6-5 (G)



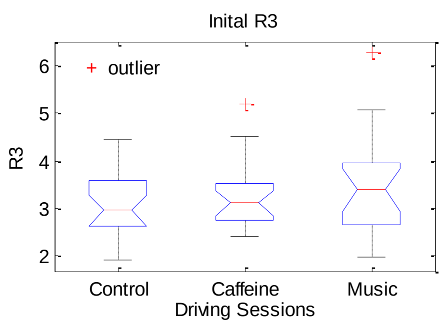
(A) (B)

Figure 44 R2 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.

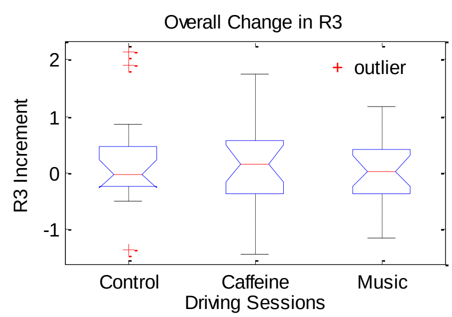
The initial group means of R3 were 3.084 for the control session, 3.3073 for the caffeine session, and 3.4865 for the music session. A one-way ANOVA analysis suggested that R3 were not significantly different at the beginnings of the three driving sessions [F(2,57,59)=1.2084, p=0.3062]. Multi-comparison were performed using the Tukey test, showing that no significant difference in initial R3 between any two of the three driving sessions. This was also shown in Figure 45(A).

A series of paired student *t*-tests were performed to examine whether R3 was significantly changed after each 120-minute driving session. The results showed no significant changes in any of three sessions [p=0.3078, *t* = -1.05, CI=(-0.5544, 0.1845) for the control session; p=0.4362, *t* = -0.80, CI=(-0.4561, 0.2049) for the caffeine session;

p=0.9069, t = 0.12, CI=(-0.2588, 0.2899) for the music session]. The increments of R3 after completing each driving session, ${}_{T}^{s}\Delta R3^{m}$, were calculated using Equation 6-5 (G). Group average increments of R3 were 0.185 for the control session, 0.1256 for the caffeine session, and 0.0155 for the music session. Further analysis, using One way ANOVA, revealed that the increment was not significantly different among the three driving session [F(2, 57,59)= 0.4343, p=0. 6499]. Multi-comparison using the Tukey test revealed that there was no significant difference in R3 increments between any two of the driving session. The results were also shown in Figure 45(B).



(A)



(B)

Figure 45 R3 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.

In summary, the ratio of the summation of theta and alpha spectrum over beta spectrum, R3, were initially similar at the beginnings of the three driving sessions. After each 120-minute driving session, R3 was not significantly changed. The increments (overall changes) of R3 after the driving session were not significantly different among the three driving sessions.

R4 – (theta + alpha)/(beta +alpha). The first indicator was denoted as ${}_{T}^{s}R4_{n}^{m}$ and obtained using Equation 6-2 (H), representing the ratio of the current summation of theta and alpha spectrum over the summation of beta and alpha spectrum. The value reflected the current status of the m^{th} subject at the n^{th} subsection (within 2 seconds) during the T^{th} Lane Keeping Task in the s^{th} driving session (1st = control session, 2nd =caffeine session, and 3rd = music session). The average fatigue levels during the s^{th} Lane Keeping Task (5 minutes) in the s^{th} driving session was denoted as ${}^{s}_{T}R4^{m}$ and calculated using Equation 6-3 (H). The average status during the Lane Keeping tasks of an individual subject was plotted in Figure 46(A): red circles for the control session, blue starts for the caffeine session, and black triangles for the music session. From the plot, no absolute change was observed in each driving session..

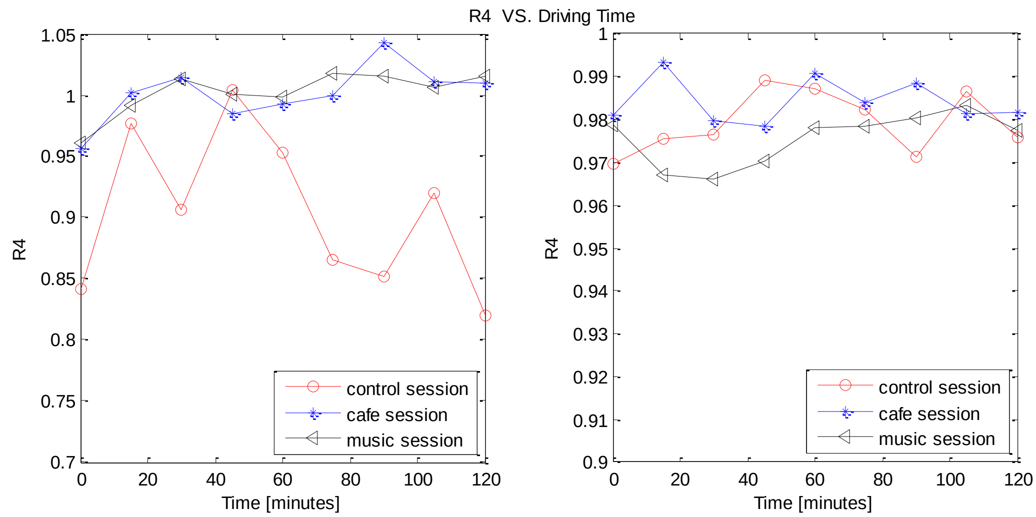
$$ {}^{s}_{T}R4_{n}{}^{m} = {}^{s}_{T}A\theta_{n}{}^{m} \Big/ {}^{s}_{T}A\beta_{n}{}^{m} $$ Equation 6-2 (H)

$$ {}^{s}_{T}R4^{m} = \frac{1}{150}\sum_{n=1}^{150} {}^{s}_{T}R4_{n}{}^{m} $$ Equation 6-3 (H)

$$ \overline{{}^{s}_{T}R4} = \frac{1}{20}\sum_{m=1}^{20} {}^{s}_{T}R4^{m} $$ Equation 6-4 (H)

$$ {}^{s}_{T}\Delta R4^{m} = {}^{s}_{9}R4^{m} - {}^{s}_{1}R4^{m} $$ Equation 6-5 (H)

The group mean of R4 during each Lane Keeping Task was calculated for all twenty subjects using Equation 6-4 (H), and denoted as $\overline{{}^{s}_{T}R4}$. The group means of R4 were plotted in Figure 46(B), again, red circles for the control session, blue starts for the caffeine session, and black triangles for the music session. From the plot, no absolute change was observed in each driving session. The initial group means of R4 were 0.9698 for the control session, 0.9811 for the caffeine session, and 0.9787 for the music session. A one-way ANOVA was performed and the result showed that R4 at the beginning of the three driving sessions were not significantly different [F(2,57,59)=0.3331, p=0.7181], the result was also shown in Figure 47(A). Multi-comparison was performed using the Tukey test, showing that there was no significant difference of R4 between any two of the three driving sessions at the beginnings.



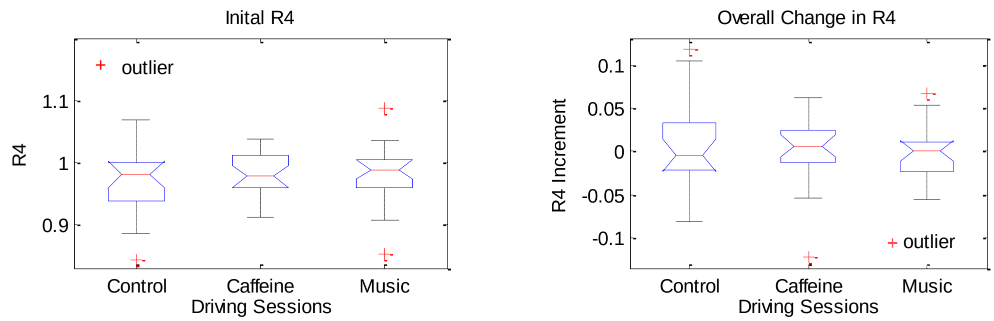
(A) (B)

Figure 46 R4 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.

A series of paired student *t*-test were performed to examine whether R4 was significantly changed after each 120-minute driving session. The results showed no significant changes in any of three sessions [p=0.6196, t = -0.50, CI=(-0.0306, 0.0187) for the control session; p=0.9554, t = -0.06, CI=(-0.0201, 0.0190) for the caffeine session; p=0.8331, t = 0.21, CI=(-0.0126, 0.0154) for the music session]. The increments of R1 after completing each driving session, ${}_{T}^{s}\Delta R4^{m}$, were calculated using Equation 6-5 (H). Group average increments of R4 were 0.0059 for the control session, 0.0005 for the caffeine session, and -0.0014 for the music session.

Further analysis, using a one-way ANOVA, revealed that the increment was not significantly different among the three driving sessions [F(2, 57,59)=0.1618, p=0.851].

Performance of multi-comparison using the Tukey test revealed that there was no significant difference of the increment in R4 between any two of the three driving sessions. The results were also shown in Figure 47(B).



(A) (B)

Figure 47 R4 as a fatigue indicator against driving time for (A) an individual subject, and (B) for the whole group.

In summary, the ratio of the summation of theta and alpha spectrum over the summation of beta and alpha spectrum, R4, were initially similar and showed no significant difference at the beginnings of the three driving sessions. After each 120-minute driving session, R4 were not significantly changed. The increment (overall changes) or R4 after the driving sessions were not significantly different among the three driving sessions.

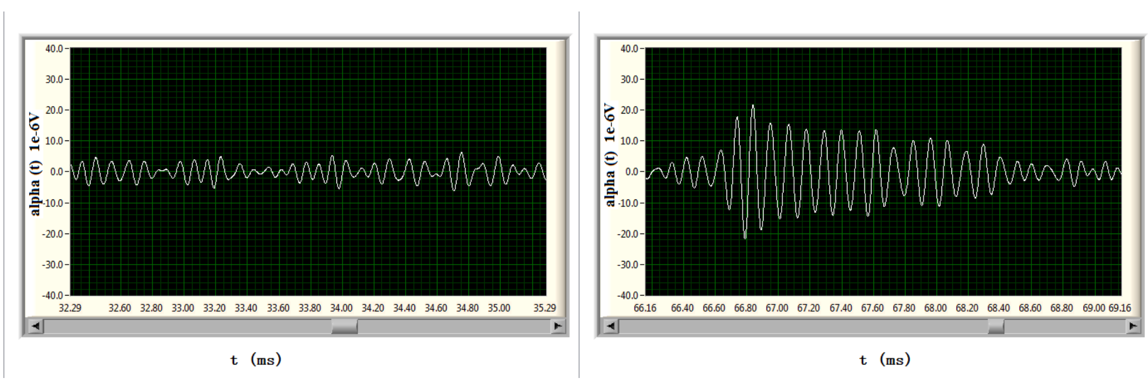
Previous analysis on the SDFS and driving performance suggests that subjective fatigue levels are increased and driving performance is deteriorated after prolonged driving. It is expected that EEG also changes significantly with increased fatigue levels after 120-minute driving tasks. However, the results obtained from the second experiment indicate that none of the four EEG component activities (power spectrum) nor the four ratios of slow wave to fast wave suggested by Jap, et al. [77] have changed significantly after completing the driving sessions. This is a surprising result, as some other researchers [13, 63, 77] have suggested that EEG power spectrum analysis and ratios of these spectrum are useful indicators for driver fatigue.

When the plot of the SDFS against driving time in Figure 16(B) is reexamined, it can be seen that the average SDFS is highest at the end of the control session, but less than 45. Considering the minimum and maximum possible SDFS are 11 and 110 respectively, this is really a relatively low score, not even close to 50% of maximum score, which is 60.5. Keeping this in mind, it is understood that although the subjects have reported significant subjective fatigue increase, on average their fatigue levels are still low at the end of the experiment. The driving performance is also degraded gradually. However, the subjects can still drive safely by the end of the experiment. The moderate SDFS and non-seriously deteriorated driving performance suggests that the average driver fatigue has not reached a very high level at which driving safety can absolutely be interfered with. The EEG based variables cannot reflect these degrees of changes in driver states. One possible reason is that driver fatigue has not increased enough to be estimated by these EEG based variables. This is similar to those driving performance variables (such as means and standard deviation of lateral position) that have not shown significant changes after 120-minute driving task.

6.3.3 EEG for a very fatigued subject

On the other hand, when the EEG signal was examined for individuals, obvious changes have been observed for subjects who showed a very large fatigue increase. A large number of α waves have been observed when the SDFS reached around 80. The difference between initial and final EEG signal are displayed in Figure 48.

The initial SDFS of the individual subject is 25. The α wave showed amplitude of 4 mv and intermittence of 0.1 ms, as shown in Figure 48(A). After completing the two hour control driving session, the final SDFS increased to 83. The average amplitude of the α wave increased to 15 mv (with maximum of 20 mv), and this increase in α wave continued for 2 ms, as shown in Figure 48(B). During the control session, the α wave shown in Figure 48(B) was often accompanied with a drift of the vehicle from center of the lane to the edge of the lane. At the end of the experiment, the subject reported micro-sleep near the end of the control session. However, only two subjects showed the α wave with such pattern, the other subject had a SDFS of 74 at the end of the control session. All the other subjects showed normal EEG signals throughout the driving sessions. Therefore, the observation is not conclusive. However, it provides a research direction for the future.



(A) (B)

Figure 48 EEG: 3 milliseconds of α waves for an individual subject (A) at the beginning of the control session (SDFS = 25), (B) at the end of the control session (SDFS = 83)

6.4 Summary of the 2nd experiment

The 2nd experiment has examined the effectiveness of two popularly used fatigue countermeasures: caffeine and music. The data analysis on the SDFS shows that the two methods are equivalently effective in reducing feelings of fatigue in the 120-minute simulated driving task. On the other hand, driving performance deteriorated similarly in the music and control sessions; while caffeine helps the subjects inhibit deterioration of driving performance. This is probably due to the factor that caffeine stimulates the central nervous system to maintain alertness throughout the caffeine session. The music probably also has distracted the subjects from the driving task while providing stimulation to keep them alert, therefore, driving performance is deteriorated. However, it must be noticed that the subjects have maintained sufficiently good driving performance to drive safely. This suggests that both methods are helpful to counter with driver fatigue but in different ways: caffeine helps to reduce subjective fatigue and maintain good driving performance, and music helps to reduce subjective fatigue only. In addition, the EEG signal analysis does not show significant changes in the four bandwidth components and the four ratios of slow wave to fast wave. This probably is due to relatively low levels of the average fatigue of the group. When the EEG signal of an individual subject with high level of fatigue is examined, the amplitude of the alpha component increases significantly and a special pattern has been observed. Therefore, the EEG signal should be further examined in the future work, in which the subject experiences more severe driver fatigue.

Chapter 7 Conclusion

The aim of this project is to experimentally investigate variations of driver fatigue, driving performance, and effectiveness of fatigue countermeasures, therefore to better understand the mechanism of driver fatigue. Two experiments have been conducted. The first experiment employed a specially designed driver fatigue questionnaire to quantitatively estimate the subjective fatigue levels of the subjects. Driving performance was estimated by sixteen parameters related to steering wheel control, lateral position control, and speed control abilities. A co-relationship between this new fatigue indicator and driving performance has been observed. This linear relationship may be helpful in predicting driver fatigue levels when driving performance is known, and vice versa. Another subjective assessment tool (Stanford Sleepiness Scale) and the psychomotor test (Divided Attention Test) were used in the first experiment to reflect driver states. The second experiment examined two of the most frequently used fatigue countermeasures, by comparing with the control driving session without any countermeasure. The new subjective driver fatigue indicator and the sixteen driving performance parameters were also used to estimate the driver states. EEG signals were employed to reflect brain activity as an additional fatigue assessment. The result of the second experiment revealed the effectiveness of and the differences between these two methods.

In the first part of the project, a questionnaire, the Driver Fatigue Questionnaire has been developed particularly for the driver. The questionnaire includes 12 items which represent physical symptoms, driving behaviors, perception, tiredness, and driver capacity. The driver fatigue levels were quantitatively estimated by the SDFS obtained from the questionnaire. Thirty three subjects completed the experiment. Their subjective fatigue levels were estimated using the SDFS and the SSS, the residues of driver capacity and reaction time of Divided Attention Tests were also collected.

The results showed that the SDFS increased rapidly after completing the 1st driving session and also increased gradually during the 2nd and 3rd driving sessions. Interestingly, trend of decreases in the SDFS were observed after short breaks between driving sessions, indicating fatigue recovery, although the break was only about 3 minutes long. SDFS obtained by the questionnaire were similar to the sleepiness ratings estimated by the SSS, but somewhat different. Both measurements increased with driving time. However, the results of the SSS remained almost constant during the last two sessions, while the SDFS increased gradually and continuously during the last two sessions. This difference between the two subjective assessment tools may suggest that the SSS alone is not sufficient to reflect changes in the fatigue level of drivers, because the SSS only reflects the sleepiness of the subject. However, driver fatigue is much more complex, and involves physical symptoms, driving behaviors, perception, tiredness, and driver capacity. A more sophisticated indicator (such as the SDFS) reflecting all aspects of driver fatigue may be able to quantify subjective fatigue levels in multiple dimensions. The questionnaire also suggested that the residual driving capacity decreased with prolonged driving task. This result also agreed with expectation.

Driving performance was measured in three groups of parameters, examining ability in steering wheel control, lateral position control, and speed control. Evidence showed impairment in driving performance with prolonged driving tasks. Overall impairment was indicated by significant increases in two group means (means of lateral velocity and longitudinal velocity) and five standard deviations (standard deviations of steering wheel angle, yaw rate, lateral velocity, lateral acceleration, and longitudinal velocity). This may suggest that standard deviations are more sensitive to changes in driver fatigue than the means. For example, the group means of steering wheel angle and yaw rate did not show significant change after three driving sessions. However, the standard deviations of steering wheel angle and yaw rate showed significant increase after three driving sessions. The result suggested that after completing three driving sessions the subjects were still able to maintain the steering wheel in the natural positon on average; however, variance of the steering wheel angular position became greater after the prolonged driving task. The result also suggested that the subjects were able to keep the vehicle traveling on a straight line; however, the subjects changed the direction more rapidly. With higher level of driver fatigue, the abilities of handling the steering wheel and maintaining the vehicle direction were degraded. This might have resulted from a slowed information processing rate, which directly related to fatigue levels. On the other hand, inter-sessional impairment was observed only on three parameters (the mean of lateral velocity, and mean and standard deviation of longitudinal velocity). This may suggest these three parameters were very sensitive to variation in driver fatigue levels; therefore, the changes were significant even after 45-minute driving tasks.

Reaction time on the divided attention task decreased throughout the experiment, which was different from expectation and the observation from other researchers [102]. Learning effects might be one of the major causes of this reduction of reaction time. Distraction from the driving task might be another major cause of this change in reaction time. This might suggest that reaction time from the divided attention test was not a good measure of driver fatigue.

Changes in driving performance were also compared with the changes in driver fatigue level. The curve fit showed in Figure 12 suggested that general degradation in driving performance might be mathematically expressed by the SDFS, and vice versa.

Radar diagrams were created to present driver fatigue and driving performance in multi aspects. The five sub scores of driver fatigue plotted in the radar diagram not only reflected the severity of each fatigue aspect, but also revealed characteristics of driver fatigue the subject experienced. Therefore, the appropriate fatigue countermeasures can be employed by the fatigued driver to avoid fatigue related accidents. The radar plot of driving performance reflected degradation of each vehicle controlling ability. Therefore, an appropriate driving assistant device/system (such as lane position maintaining system and adaptive cruise control system) can be activated to help the operator to avoid accident.

From the first experiment, it can be concluded that (1) the SDFS is a good driver fatigue indicator, because it quantitatively reflects multiple aspects of driver fatigue, (2) sixteen parameters chosen for driving performance estimation are sensitive to variation in driver fatigue, (3) a mathematical model can be used to represent the relationship between driver fatigue levels and driving performance, (4) reaction time examined on the divided attention test during the driving task may not be a good estimation of driver fatigue, because reaction time can be influenced by fatigue levels, mental workload, and other factors, (5) multi-dimensional representation of driver fatigue and driving performance can help the driver to choose appropriate fatigue countermeasures and activate an appropriate driving assistant system to avoid fatigue related accidents.

The second experiment investigated the effectiveness and differences of two frequently adopted driver fatigue countermeasures. Each of 20 drivers completed three 120-minute driving sessions (control, caffeine, and music). Driver fatigue was quantified in a 15-minute interval using the SDFS developed in the first experiment, and driving performance was evaluated using 16 driving performance parameters. The results showed that initial driver fatigue and driving performance were not significantly different among the three sessions. Therefore, any differences in changes in the SDFS and deterioration of driving performance were caused by the different fatigue countermeasures adopted by the driver. Although the SDFS increased significantly after each driving session, the increment was greatest after the control session, medium after the music session, and smallest after the caffeine session. The increment of the SDFS in the control session was significantly greater than the other two sessions, and not significantly different between the music and caffeine sessions, indicating the two methods were almost equally effective in reducing subjective fatigue levels. On the other hand, deterioration of driving performance was also greatest for the control session, medium for the music session, and least for the caffeine session. However, the increment of deterioration of driving during the caffeine session was significantly less than both control and music sessions, and the increment of deterioration was not significantly different between control and music sessions. This may suggest that although listening to music effectively inhibits the increase in subjective fatigue, it may not be able to effectively inhibit deterioration of driving performance. On the other hand, consuming caffeine effectively inhibits both increase in subjective fatigue and deterioration of driving performance. This may be because caffeine stimulates the central nervous system by blocking adenosine receptors and increasing the neurotransmitter dopamine. However, music probably only provides external stimulation that reduces boredom of the driving task, and may also introduce distraction to drivers.

The results of the second experiment suggest that both consuming caffeine and listening to music can help the driver reduce subjective fatigue levels, but consuming caffeine is more effective than listening to music in maintaining driving performance. It is necessary to study the cause of the difference between the two fatigue counter-measures. The study also provides a useful protocol to quantitatively study the effects of fatigue countermeasures. From the results of this study, we also have found the 16 driving performance parameters are able to accurately and sensitively reflect driver fatigue levels. A driving performance monitoring system based on these parameters may be promising. On the other hand, the EEG signal, which has been proposed to be a good indicator of fatigue, did not show any significant variation on average. Examination on initial EEG indicators suggested that the subject started each of three sessions at similar states. Examination of changes in EEG indicators within each driving session also showed no significance. This indicates that on average the EEG indicators are not as sensitive to state changes of the drivers as the SDFS and driving performance parameters. However, a large increase in amplitude of α wave and changes in its pattern have been observed for individuals who reported a very high SDFS and micro-sleep. This suggests a new direction of study related to driver fatigue: investigation of EEG signal changes in high fatigue levels for drivers.

From this project, we have found that (1) the SDFS obtained from DFQ can quantitatively estimate driver fatigue levels in various conditions, including prolonged driving tasks with breaks or without breaks, with fatigue countermeasures adopted or not, etc.; (2) sixteen driving performance parameters can reflect driver abilities to control the vehicle; (3) the mathematic relationship between the SDFS and driving performance enable drivers to predict driving performance when the SDFS is known, and vice versa; (4) radar diagrams of driver fatigue and driving performance estimation may help drivers better understand their conditions to employ appropriate countermeasures and a driver assistant system to avoid accidents; (5) two fatigue countermeasures – caffeine and listening to music – are effective in maintaining low fatigue level during prolonged driving task; (6) caffeine can reduce feelings of tiredness while improve driving performance, because caffeine stimulates the central nervous system; (7) listening to music only reduce feelings of tiredness while does not improve driving performance, maybe due to additional distraction to drivers.

However, it must be noticed that there are some limitations of the current study. The first limitation is that the experiments are conducted in a simulated driving environment, and it involves only highly simplified road scenarios. The eliminated factors, such as traffic jams and bad road surface conditions have potential effects on driving performance and mental workload, and have various impacts on driver fatigue levels. To validate the result on the real traffic condition, an on-road experiment may be conducted in the future.

Another limitation of the current study is that the subjects are not particularly districted into regular coffee consumers and non-regular coffee consumers during the second experiment. It is unknown whether four hour inhibiting from caffeine would have significant impacts on regular coffee consumers or not. However, in the current study, none of the subjects reported negative impacts on either fatigue levels or driving performance. The current study focuses on the effects of countermeasures on the subjects in general. To investigate the difference between the regular coffee consumers and non-regular coffee consumers, another experiment must be conducted. However, regardless the subject is a regular coffee consumer or non-regular consumer, after four hour inhibiting from caffeinated drink, the intake of caffeine at the beginning of the caffeine driving session have stimulating effects on most subjects, as observed in the second experiment. The significant difference in driving performance between the caffeine sessions and control sessions confirmed this stimulating effect. The study also asked the subject to restrain from cigarette for four hours, and the subject could not smoke during the experiment. The subjects were not districted into smokers and non-smokers. The impact of restrain from cigarette on the regular smokers should be investigated in the future.

In the study, the data were assumed to be normally distributed. However, from the plots such as the initial and first data set for Figure 9 (B), the data showed a possible skewness. To check the skewness, a method described in [105] was used. The results suggested that the data were normally distributed, as shown in Figure 49. However, the method also suggested that the skewness was not reliable with small sample size. To determine whether the data is skewed, a very large sample is necessary.

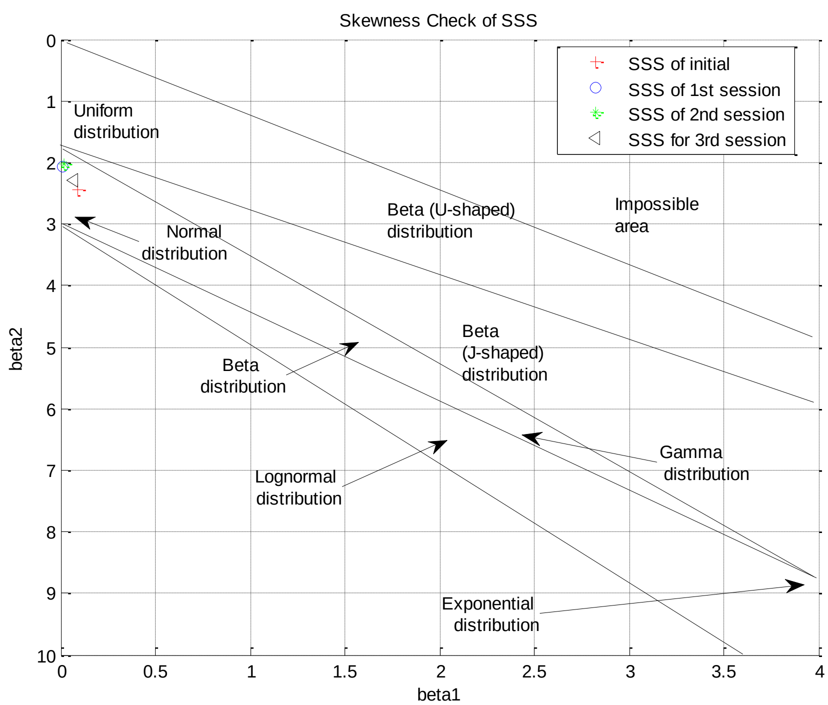


Figure 49 Skewness of the SSS, Regions in the β1, β2 plane for various distributions, regenerated from [105] page 350.

Based on the current study, we may suggest that the DFQ and the SDFS can be used in other driver fatigue related studies, such as in on-road experiments, to examine whether this subjective assessment tool can be used in real driving conditions. Regarding fatigue countermeasures, the protocol developed in the second experiment may be applied to examine other methods adopted by drivers to quantitatively estimate the effectiveness. The sixteen driving parameters used in this project have shown sensitivity to the fatigue levels and fatigue countermeasures. A driving performance monitoring system might be useful in assisting drivers to keep road safety, if these sixteen driving parameters can be recorded and analysis in real time. For example, an algorithm or an android application can be developed, which can collect the data from sensors installed on the steering wheel and other parts of the vehicle, then online driving performance can be displayed on a screen as a radar plot. This will remind the driver how good his/her driving performance is and what action he/she needs to take to drive safely. The history of driving performance, if recorded, may be also very useful. By analyzing the driving performance history of an individual, a driver school may help the driver improve his/her driving skills by providing a personal training program. The insurance company might be even more interested in looking at the driving performance history of drivers. Based on the driving performance history, the insurance can be determined for individuals. An individual can also argue with the insurance company to reduce his/her insurance by providing a good driving performance history.

Appendix A: Survey Form

Survey Form

Thank you for taking part in this research project. This survey form will help us better analyze the experiment data. The subject number is arranged in the sequence of experimental date. Your name will never be used in the presentation or publication of the results unless you specifically hope so. Any information related with this research get from you is confidential and will only be accessed by the members of the research team.

Part I – Demographic Information			
File No:		Date / Time	
Gender:	M ☐ / F ☐	Age :	
Do you have a valid driver's license?	Yes ☐ / No ☐		
How many years have you held your valid driver's license:	_______ years		

Part II - Sleep History		
1.	How much sleep did you get last night?	_______________hours
2.	When did you go to bed last time?	___:___ am/pm
3.	When did you get up today?	___:___ am/pm
4.	Do you have difficulty falling asleep? Not at all ☐ A little ☐ Quite a bit ☐ Almost always ☐	
5.	When did you last eat? Breakfast ☐ Lunch ☐ Dinner ☐ Snack ☐ ___:___ am/pm	
6.	How did you feel today compared to your usual state?	Worse … Better 1 2 3 4 5 6 7 8 9 10
7.	Did you do physical work/exercise today, and how much?	None … A great deal 1 2 3 4 5 6 7 8 9 10
8.	How tired do you feel now?	Very Alert … Very Tired 1 2 3 4 5 6 7 8 9 10
9.	What time do you feel most alert during the day?	___:___ am/pm to ___:___ am/pm
10.	What time do you feel most drowsy during the day?	___:___ am/pm to ___:___ am/pm
11.	Did you take any coffee/tea/energy drink today? If yes, please specify	Yes ☐ / No ☐ Coffee/Tea/Other ________ ______cups; ___:___ am/pm
12.	Do you smoke?	
13.	Do you drink alcoholic beverages?	Yes ☐ / No ☐
	If yes, how much did you drink today?	______cups; ___:___ am/pm

Appendix B: Questionnaire

Fatigue Assessment		
	A	
	Questionnaire for Driver Fatigue	**Check a number between 1 to 10**
1.	To what degree is the fatigue you are feeling now interfering with your ability to drive safely?	None — A great deal 1 2 3 4 5 6 7 8 9 10
2.	To what degree are you feeling ……	Awake — Sleepy 1 2 3 4 5 6 7 8 9 10
3.	To what degree are you feeling ……	Able to concentrate — Unable to concentrate 1 2 3 4 5 6 7 8 9 10
4.	If you have a headache now, rate its severity	None — A great deal 1 2 3 4 5 6 7 8 9 10
5.	To what degree are your eyes strained?	None — Very Strained 1 2 3 4 5 6 7 8 9 10
6.	How likely are you to pass a leading vehicle which is much slower than your current speed?	Pass — Not pass 1 2 3 4 5 6 7 8 9 10
7.	To what degree are you willing to pull over and have a rest?	Not at all — Very willing 1 2 3 4 5 6 7 8 9 10
8.	Are your feet sore?	Not at all — Extremely sore 1 2 3 4 5 6 7 8 9 10
9.	Are you feeling any backache?	None — A great deal 1 2 3 4 5 6 7 8 9 10
10.	Are your joints stiff?	Not at all — Extremely stiff 1 2 3 4 5 6 7 8 9 10
11.	Are you feeling any numbness?	None — A great deal 1 2 3 4 5 6 7 8 9 10
12.	How many more hours do you think you can keep driving?	_______________ hours
	B	
	Standard Sleepiness Scale (SSS)	**Circle one of the following**
13.	Feeling active, vital, alert, or wide awake	1
	Functioning at high levels, but not at peak; able to concentrate	2
	Awake, but relaxed; responsive but not fully alert	3
	Somewhat foggy, let down	4
	Foggy; losing interest in remaining awake; slowed down	5
	Sleepy, woozy, fighting sleep; prefer to lie down	6
	No longer fighting sleep, sleep onset soon; having dream-like thoughts	7
	Asleep	X

Appendix C: Letter of information / Consent

McMaster University
Inspiring Innovation and Discovery

LETTER OF INFORMATION / CONSENT

Investigating effects of driver fatigue and fatigue countermeasures on driving performance in simulated driving

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Purpose of the Study

You are invited to take part in this study on "Investigating effects of driver fatigue and fatigue countermeasures on driving performance in simulated driving." We want to conduct experiments to collect data of driver fatigue and driving performance during prolonged driving, with or without fatigue countermeasures. We are hoping to learn how driver fatigue increases and whether it can be quantified after a long period of driving. We also hope to find out how driving performance is affected by increased fatigue levels. Driving simulator is used in this experiment to minimize risks caused by driver fatigue. The experiment will be conducted from May 2013 to May 2014.

Procedures involved in the Research

You will be shown how to use the driving simulator. We will ask you for some demographic/background information, and complete either the 1st experiment or the 2nd experiment. In the 1st experiment, you will be asked to do the following two tasks:

1) Fill out a questionnaire to describe your states
2) Operate the simulator for 3 sessions, each of which lasts 40 minutes

Between sessions, you will take short breaks (3 minutes each).In the 2nd experiment, you will be asked to do the following tasks:

1) Fill out a questionnaire to describe your states (the 1st day)
2) Operate the simulator for the 1st session for 2 hours, without fatigue countermeasure (the 1st day)
3) Operate the simulator for the 2nd session for 2 hours, after drinking a bottle of Starbucks® Bottled Mocha Frappuccino® (the 2nd day)
4) Operate the simulator for the 3rd session for 2 hours, while listening the music (the 3rd day)

During each session, you will encounter various traffic situations in urban and rural environments including traffic following, passing large trucks, confronting road hazards, emergency braking, etc. We will also ask questions in the questionnaire during driving session, and you will be asked to provide answers verbally.

Potential Harms, Risks or Discomforts

The risks involved in participating in this study are minimal. You may feel uncomfortable with moving road scenarios on the screen. You may find it stressful to drive for 2 hours in driving simulator and get fatigued rapidly. You may feel uncomfortable with electrodes of EEG attached on your head. You may also feel uncomfortable to wear an ear-phone while driving.

You do not need to answer questions that you do not want to answer or that make you feel uncomfortable. You can withdraw (stop taking part) at any time. I describe below the steps I am taking to protect your privacy.

Potential Benefits

We hope to learn more about driver fatigue and its effects on driving performance, and effectiveness of various fatigue countermeasures. I hope that what is learned as a result of this study will help us to better understand how fatigue accumulates during driving tasks and how it deteriorates driving. This could help drivers avoid driving with fatigue and improve road safety. You may learn about how you experience fatigue when driving and effectively manage driver fatigue.

Payment or Reimbursement

You will receive $10 for every 1 hour simulated driving. If you cannot complete the whole driving session, compensation will be calculated based on 15 minutes interval. If you choose to withdraw, you will still get paid for the hours that you spent on the driving simulator.

Confidentiality

You are participating in this study confidentially. We will not use your name or any information that would allow you to be identified. No one but me (and other members of the research team such as the research assistant) will know whether you participated unless you choose to tell them.

Participation and Withdrawal

Your participation in this study is voluntary. It is your choice to be part of the study or not. If you decide to be part of the study, you can stop (withdraw), from the experiment for whatever reason, even after signing the consent form or part-way through the study. If you decide to withdraw, there will be no consequences to you. You can withdraw your data one month after you complete the experiment. In cases of withdrawal, any of your data that has been collected will be destroyed unless you indicate otherwise. If you do not want to answer some of the questions you do not have to, but you need to quit the study.

Information about the Study Results

I expect to have this study completed by approximately one year. If you would like a brief summary of the results, please let me know how you would like it sent to you.

Questions about the Study

If you have questions or need more information about the study itself, please contact me at:
lius46@mcmaster.ca, or through Phone 905-525-9140 Ext. 24544.

This study has been reviewed by the McMaster University Research Ethics Board and received ethics clearance.
If you have concerns or questions about your rights as a participant or about the way the study is conducted, please contact:

McMaster Research Ethics Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Research Office for Administrative Development and Support
E-mail: ethicsoffice@mcmaster.ca

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CONSENT

- I have read the information presented in the information letter about a study being conducted by ShiXu Liu, of McMaster University.
- I have had the opportunity to ask questions about my involvement in this study and to receive additional details I requested.
- I understand that if I agree to participate in this study, I may withdraw from the study at any time up to **one month** after I complete the experiment.
- I have been given a copy of this form.
- I agree to participate in the study.

Signature: ________________________________

Name of Participant (Printed) ______________________________

...Yes, I would like to receive a summary of the study's results.
Please send them to this email address ____________________________________
Or to this mailing address: ____________________________________
____
____

... No, I do not want to receive a summary of the study's results.

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Appendix D: Operating Characteristic Curves

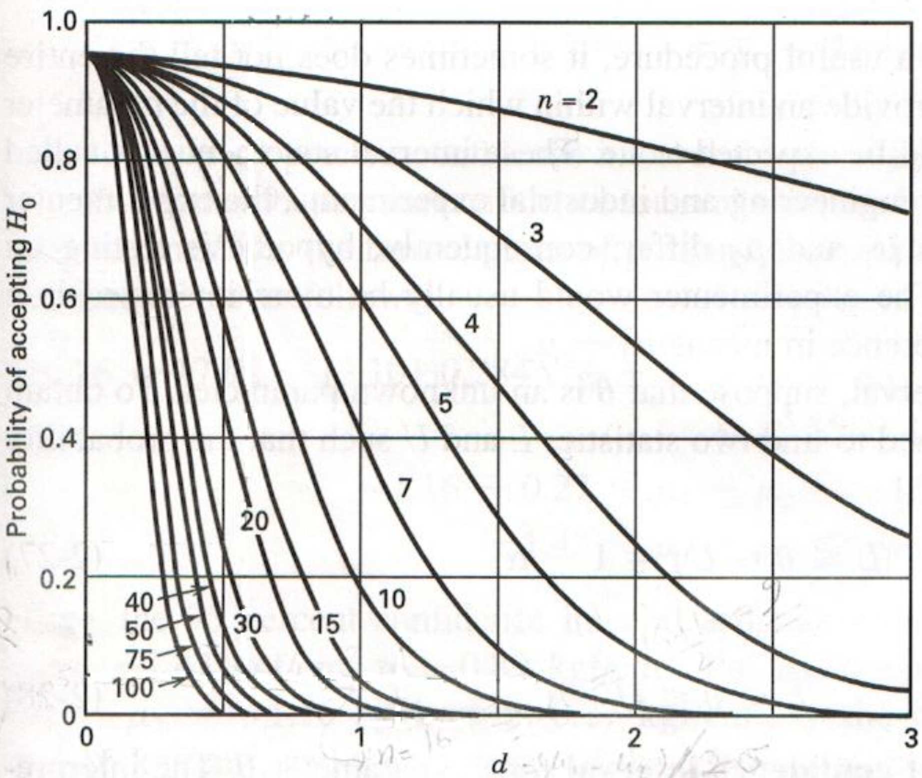

Figure 2-12 Operating characteristic curves for the two-sided *t*-test with $\alpha = 0.05$. (Reproduced with permission from ''Operating Characteristics for the Common Statistical Tests of Significance,'' C. L. Ferris, F. E. Grubbs, and C. L. Weaver, *Annals of Mathematical Statistics*, June 1946.)

Operating Characteristic Curves adopted from [99] Page 41

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