RESEARCH ON HEART RATE AND EYE MOVEMENT AS INDICATORS OF DRIVERS' MENTAL WORKLOAD

Rui Fu

Professor, Key Laboratory of Automotive Transportation Safety Technology, Ministry of Transport, PRC, Chang'an University, Xi'an 710064, Shaanxi, China, e-mail: furui@chd.edu.cn

Yingshi Guo

Professor, School of Automobile, Chang'an University,
Xi'an 710064, Shaanxi, China, e-mail: guoys@chd.edu.cn

Yang Chen

Graduate Student, School of Automobile, Chang'an University,
Xi'an 710064, Shaanxi, China, e-mail: oldcat_17@163.com

Wei Yuan

Associate Professor, School of Automobile, Chang'an University,
Xi'an 710064, Shaanxi, China, e-mail: yuanwei@chd.edu.cn

Yong Ma

PhD Student, School of Automobile, Chang'an University,
Xi'an 710064, Shaanxi, China, e-mail: ahmayong@163.com

Jinshuan Peng

PhD Student, School of Automobile, Chang'an University,
Xi'an 710064, Shaanxi, China, e-mail: pengjinshuan@sina.com

Qiong Zhang

PhD Student, School of Automobile, Chang'an University,
Xi'an 710064, Shaanxi, China, e-mail: zhangqiong79@tom.com

Chang Wang

PhD Student, School of Automobile, Chang'an University,
Xi'an 710064, Shaanxi, China, e-mail: wcwc209@163.com

ABSTRACT

In this research, 16 of 24 car drivers, including 8 experienced and 8 novice drivers, were recruited as participants. In the tests, when diving on an urban road, the participants' heart rates were recorded by use of a KF2 physiological monitor, and eye movement data were collected by use of an EyeLink Ⅱ eye movement tracking device. The test road was divided into 27 segments, including non-intersection roads (divided by central reservation, barrier or central line), intersections, and overpass / underpass interchanges. Taking the fluctuating rate of heart rates, the square root mean square of the difference between successive rhythm-to-rhythm (RR) intervals (RMSSD), and low frequency (LF) as indicators of a driver's mental workload, the influences of road section types and driving experience upon drivers' mental workload were analyzed, and the correlation between drivers' eye movement and electrocardio indicators was explored. The research results indicate that drivers' mental workload is affected by road section types and driving experience. When driving on the same road, the mental stress upon the experienced driver group is lower than that of the novice driver group. By analyzing the correlation between eye movement and heart rate, it is found that a driver's mental workload has much more influence on the saccade behavior than on fixation (gaze) behavior.

Keywords: heart rate, eye movement, mental workload, driving experience, saccade behavior

INTRODUCTION

When steering a car and maneuvering it through various traffic situations, high demands are placed on drivers (Baldauf, Burgard, & Wittmann, 2009). These high demands are generally called mental workload. Mental workload has been shown to play a substantial role in driving safety. The principal reason for measuring workload is to quantify the mental effort needed to perform tasks. This data is useful for predicting operator and system performance in various fields. Once the mental workload reaches an unacceptable level, driving safety may suffer (Liu, Zhang, & Sun, 2007; Wong & Huang, 2009). Many researchers have studied mental workload, in regard to its measurement (Baldauf, et al., 2009; Chen, 2009; De Waard, 1996; Guo, 2009; Mehler, Reimer, Coughlin, & Dusek, 2009), its relationship to the quality of highway geometric design (Heger, 1998), and so on. However, there are few formal definitions of it (Cain, 2007). Considering the internal demands that compete for an operator's resources, an appropriate definition of mental workload is: mental workload is the demand placed on an operator's mental resources used for attention, perception, reasonable decision-making and action (Wiki, 2010).

Physiological measures of mental workload can be successfully used in driving-related human factors research (Brookhuis & De Waard, 2001; Mehler, et al., 2009; Wilson, 2002). Various heart rate measurements (such as heart rate, its variability, and resulting blood pressure) have been reported to be sensitive to workload. These measurements are relatively easy to employ

unobtrusively both in the laboratory and in the field. The accuracy of heart rate readings can be affected by respiration, physical work and emotional strain, so unique measurements are needed to isolate the contribution of mental workload.

Physiological measurements of workload are derived from the operator's bodily functions. Several relevant indicators are generally used in mental workload evaluation, including (Orsila, et al., 2008; van Amelsvoort, Schouten, Maan, Swenne, & Kok, 2000; Wiki, 2010):

l   Heart rate (HR). This has been used in several aviation-related evaluations both in a simulator and in actual flight operations. Studies show that heart rate tends to increase in the most demanding phases of flight.
l   Heart Rate Variability (HRV) over time is also used as a measure of mental workload. The basic assumption is that the higher the workload the lower the HRV. In other words, the more the operator exerts effort the more regular the heart rate. A decrease in power in the mid-frequency band, also called the 0.10 Hz component, has been shown to be related to mental effort and task demand. One of the main limitations of heart rate spectral measurements is that they can be only used in association with a detailed task observation and analysis because these measurements are very sensitive to slight variations in workload.
l   The square root mean square of the difference between successive rhythm-to-rhythm (RR) intervals (RMSSD) describes short-term HR variations. A low value indicates high stress (Orsila, et al., 2008).

Research from cognitive psychophysiology has shown that interval fluctuations between consecutive heart beats (or RR interval) are sensitive to cognitive processing demands, and heart rate usually increases during mental tasks, whereas heart rate variability (HRV, properly heart period variability) decreases consistently with mental load (Jorna, 1992). The most commonly used HRV parameters in earlier studies have been HR (Brookhuis, De Vries, & De Waard, 1991; Brookhuis & De Waard, 1993), spectral parameters such as low frequency (LF) power components of the HRV spectrum, high-frequency (HF) power and LF/HF ratio. LF is connected with the heart's parasympathetic and sympathetic activity (Lord, et al., 2001).

Eye movement measurements can be used to support these physiological measurements. With a modern eye movement tracking device, a number of measurements of eye activity can be taken unobtrusively, such as: horizontal and vertical eye movement (extent and speed), blink activity (duration, latency and frequency), fixation (gaze) duration and saccade, point of fixation and pupil diameter (Ma, 2006; Yuan, 2008).

Although ocular measurements are sensitive to mental demands, they are also sensitive to other factors; in particular, they are sensitive to fatigue. In order to assess the effects of mental workload on visual search and decision making, Recarte & Nunes (Recarte & Nunes, 2003) analyzed 12 car drivers' pupil diameter, effort ratings, spatial fixation variability, and fixations on

the speedometer and mirrors in real traffic conditions. Mental workload was manipulated by having participants perform several mental tasks while driving. It was found that the impairment produced by mental tasks was due to late detection and poor identification more than to response selection. Verbal acquisition tasks were innocuous compared with production tasks, and complex conversations, whether by phone or with a passenger, were found to be dangerous for road safety. In a motorbike riding simulation study, Di Stasi et al (Di Stasi, et al., 2009) found that risk-prone individuals showed specific patterns of risky behavior and that the peak values of saccadic velocity and subjective mental workload were both reliable indicators of risk proneness. Mental workload was higher for participants who had a poor awareness of risk factors, probably due to a lack of conscious awareness of specific cues indicating dangerous scenarios.

A driver's mental workload can be influenced by many factors. With laboratory-equivalent modern driving simulator environments, it allows full control with respect to environmental conditions, scenarios and stimuli, and enables physiological measurement of mental workload such as heart rate and brain activity. Many current studies on a driver's mental workload are based on driving simulator results (Brookhuis & De Waard, 2010; Hoogendoorn, Hoogendoorn, Brookhuis, & Daamen, 2010; Lenneman & Backs, 2009, 2010). However, the difference in a driver's behavior and mental workload between a simulated environment and a real traffic situation cannot be ignored.

Rather than carrying out tests in a simulated environment, for this paper, we carried out research in real situations, including non-intersection roads, intersections, and interchanges. We controlled two kinds of factors on mental workload: different road types and different degrees of driving experience. The heart rate readings and eye movement readings were recorded during the real road driving tests. In regard to heart rate readings, we focused on three indicators of HRV to analyze variation in mental workload: first, fluctuating rate of heart rates; second, a time domain parameter RMSSD; third, a frequency domain parameter LF. In regard to eye movement readings, we focused on the fixation duration, saccade amplitude and saccade velocity (average and peak).

METHOD

Test Road Sections

Urban roadways present a complex traffic environment, including various types of roads. The typical types are intersections, interchanges, and non-intersection roads. In this paper, the non-intersection road sections have a central reservation, barrier or central line. To study the effects of different urban road section types on a driver's mental workload and visual search behavior, we selected a test road with a total length of 15 km in Xi'an, China, which includes a 7.5 km ring trunk road (speed limit 70 km/h), and a 7.5 km urban sub-trunk road (speed limit 40 km/h). The total driving time was approximately 30 minutes. This 15 km long test road contained ten types of road. Each road type is numbered as shown in Table 1.We also divided the test road

(containing ten road types) into 27 road segments, which are numbered in driving sequence (see Table 1).

Table 1　Information and numbers of road sections and segments

Road types		Number	Details	Segment number	Speed limit
Intersections	Left turn	T1	Two of 4 lanes two-way roads	8/14	
	Right turn	T2	Two of 4 lanes two-way roads	6/12/16/18/20	40km/h
	Straight ahead	T3	4 lanes and 2 lanes two-way road	4/10	
Interchanges	Overpass	T4	Straight ahead on overpass	19/22/24	
	Underpass	T5	Straight ahead on underpass	25	70km/h
	Ramp	T6	Right turn to overpass	2/27	
Non-intersection roads	Central reservation division on trunk	T7	6 lanes two-way road	1/21/23/26	70km/h
	Central reservation division on sub-trunk	T8	6 lanes two-way road	7	
	Barrier division	T9	4 lanes two-way road	3/5	40km/h
	Central line division	T10	4 lanes two-way road	9/11/13/15/17	

Participants

Totally 24 subjects were recruited from Xi'an City and accomplished the driving tests. Because the physiology data were captured in an active driving environment, some movement artifacts were also recorded, hence 8 participants were dropped from the analysis. Finally, the recordings from the rest 16 participants, which were manually reviewed and rejected the few defect data, were used in the data analysis. The 16 participants, 13 male and 3 female, were between 25 and 52 years of age, with varying driving experience and good visual acuity (including corrected visual acuity), without vascular problems. All of them had a driving experience more than 2 000 km in the past. During the actual road driving test, they drove the car independently, safely, and

energetically. According to the research of Yuan (Yuan, 2008), a driver who has a driving experience more than 50 000 km can be deem as an experienced driver. Based on this criterion, in our test, eight participants, who had a driving experience more than 50 000 km in the past, were selected as the experienced group, and the other eight as the novice group.

Apparatus and Measurements

A KF2 multi-parameter physiological detector (BodyMon Ltd., China), strapped around the chest, was used to record the participants' electrocardio readings. All recorded data were stored on an MMC MultiMedia card (see Figure 1(a)). To compare the HRV, we used the fluctuating rate of heart rates of each participant for analysis. The fluctuating rate of heart rates was calculated by taking a participant's heart rate in a state of rest in a seated position as the base line value. RMSSD (time domain indicator) and LF (frequency domain indicator) were taken as the HRV indicator that characterized a participant's mental workload.

An EyeLink Ⅱ eye movement tracking device (SR Research Ltd., Canada), a head-mounted device, was used to record the participants' eye movement data (including fixation duration, saccade amplitude and saccade velocity) during the driving tests. The EyeLink Ⅱ has a 500 Hz sampling rate of binocular eye monitoring, 0.5^{o} average accuracy, access eye position data with 3.0 msec delay, 0.01^{o} RMS resolution. The saccade event resolution is less than 0.05° microsaccades.

A 7-seater commercial car (JAC Motor, Model Refine, with manual gearbox) was used for the tests (see Figure 1(b)).
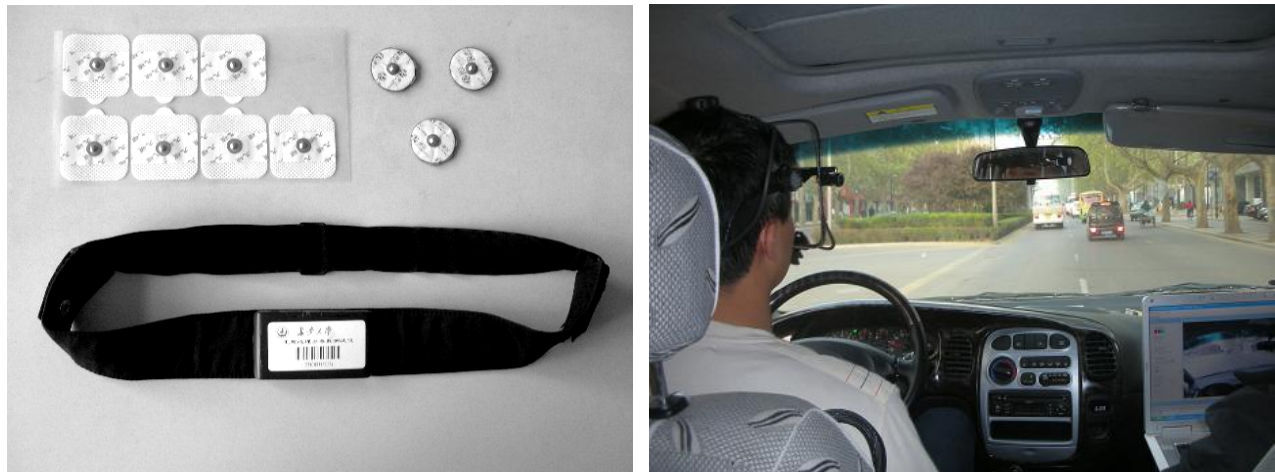
| (a) KF2 multi-parameter physiological detector and medical electrodes | (b) A participant with a head-mounted EyeLink Ⅱ eye movement tracking device driving on urban road during test |

Figure 1   Test apparatus

Procedure

All road driving tests were carried out on April within one week. In the meantime, it is neither too warm nor too cold, thus the influence of temperature on the participants physiological readings can be ignored. To diminish the illumination impact on the participants, all the tests started in the late afternoon or in the cloudy day. Additional, to ensure a similar influence of the traffic conditions on the participants, the field tests were conducted during non rush hours on workdays. Before the on-road test, the participant wore the test apparatuses, then we calibrated the EyeLink Ⅱ eye movement tracking device, and collected the heart rates of participants in a calm state as a reference. During the actual road driving test, the participant was asked to drove naturally on the designated road sections in the order of road segment from 1 to 27, as shown in Table 1. The driver's heart rates and eye movement data were recorded synchronously by the KF2 multi-parameter physiological detector and the EyeLink Ⅱ eye movement tracking device. After a participant finished the driving test, the next participant began the test, and we recalibrated the devices. After the calibration, the driving and the data recording started again. To decrease the influences difference of traffic conditions on the participants, we arranged four drivers to finish the tests on similar time in each workday. For a better analysis on the HRV indicators in the frequency domain, we used the continuous data recorded before and after the participant driving through the intersections or the interchanges, which last about 60 seconds. For non-intersection roads, the analysis data last more than 120 seconds.

RESULTS

Effects of Road Section Type on Drivers' Mental Workload

The distribution box plot of the fluctuating rate of heart rates for all participants when driving on the 27 road segments is shown in Figure 2. We carried out the one-way ANOVA for the data of the fluctuating rate of heart rates in different road segments. The results indicate that there are significant differences in the mean values of the fluctuating rate of heart rates. $F = 2.58 > F_{0.05}(26,405) = 1.52, p = 0.00005$.

The data in Figure 2 show that when driving on road segments 2,3,6,8,14,16,20,27, the mean values of the fluctuating rate of heart rates are relatively higher, in which:
l   Segment 8 and 14 are left turns at intersections;
l   Segment 6,16 and 20 are right turns at intersections;
l   Segment 2 and 27 are ramps of interchanges;
l   Segment 3 is a non-intersection road divided by barrier.
As indicated by the fluctuating rate of heart rates, a driver's mental workload is higher when driving on left turn and right turn in intersections, and on ramps of interchanges.
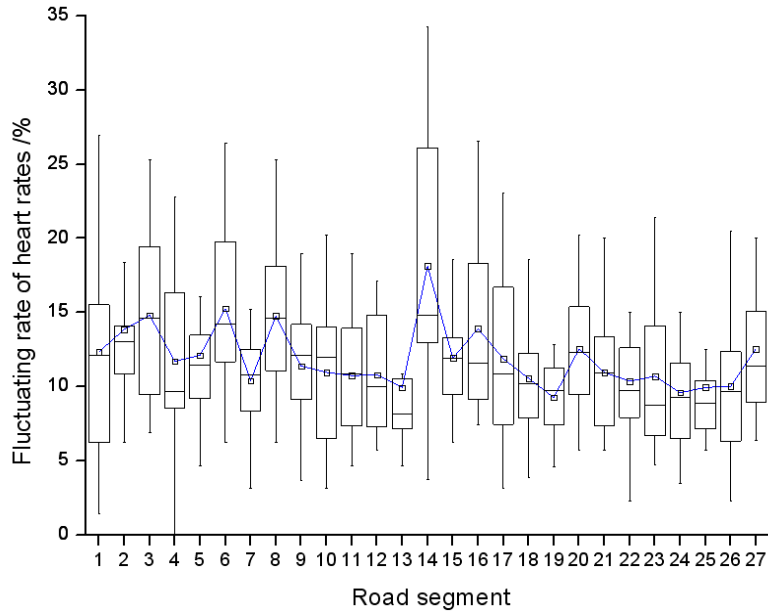
Figure 2　Distribution of participants' fluctuating rates of heart rates on different road segments

The distribution box plot of RMSSDs for all participants when driving on the 27 road segments is shown in Figure 3. We carried out the one-way ANOVA for the data of RMSSD in different road segments. The results indicate that there are no significant differences in mean values of RMSSDs. $F = 0.86 > F_{0.05}(26,405) = 1.52$, $p = 0.668$. It may be due to the fact that the samples contain participants from the experienced group and novice group, and the effect of driving experience on RMSSD is greater (see Figure 7).
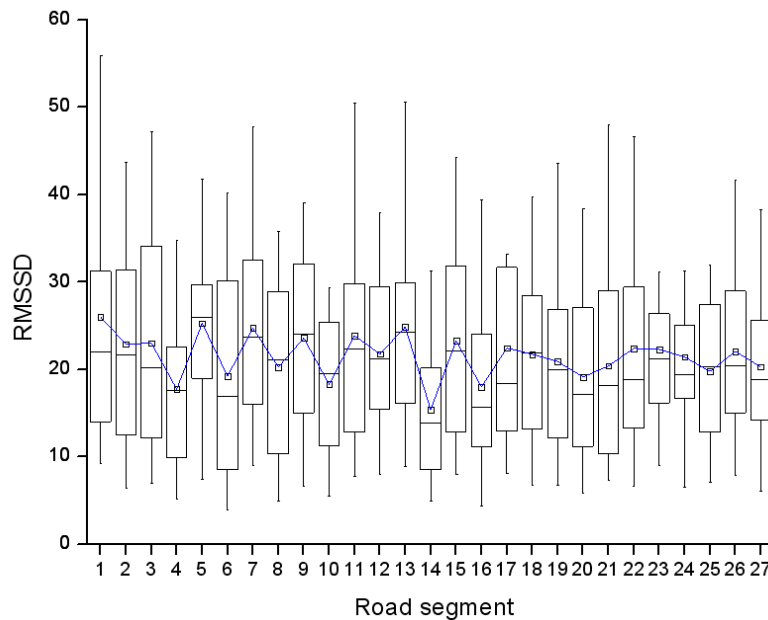

Figure 3　Distribution of participants' RMSSDs on different road segments

In Figure 3, it is shown that when driving on road segments 4,6,8,10,14,16,20,25,27, the mean values of RMSSD are relatively lower, in which:

- Segment 8 and 14 are left turns at intersections;
- Segment 6,16,20 are right turns at intersections;
- Segment 4 and 10 are straight ahead at intersections;
- Segment 25 is interchange underpass;
- Segment 27 is a ramp of an interchange.

RMSSDs indicate that a driver's mental workload is higher when driving through intersections and interchanges.

The distribution box plot of LFs for all participants when driving on the 27 road segments is shown in Figure 4. Also, we carried out the one-way ANOVA for the data of LF in different road segments. The results indicate that there are significant differences in mean values of LF. $F = 1.74 > F_{0.05}(26,405) = 1.52$, $p = 0.014$.
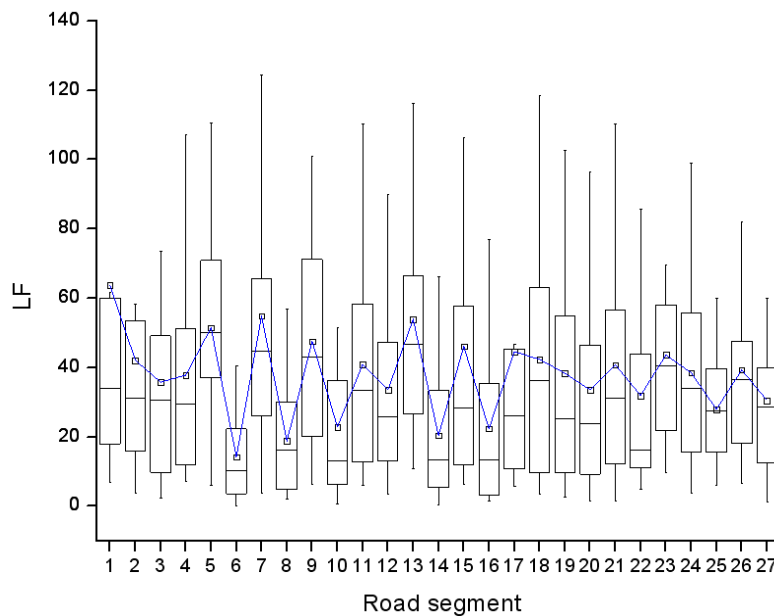

Figure 4   Distribution of participants' LFs on different road segments

Data in Figure 4 show that when driving on road segments 6,8,10,14,16, the mean values of LFs are relatively lower, and all of these segments are at intersections. It indicates that participants' mental workload is higher when driving through intersections.

As can be seen from Figures 2,3,4, a driver's mental workload can be characterized by the fluctuating rate of heart rates, RMSSD and LF. These three HRV indicators can reflect a driver's mental workload when driving on different urban road segments, and their characteristic results have a high consistency.

By sorting these 27 road segments into ten section types, we analyzed the effects of road section type on a driver's mental workload. The distribution box plot of the mean values of RMSSDs for all participants is shown in Figure 5, where the section types are re-sorted according to mean values of RMSSDs, and the mean values of RMSSDs are shown in Table 2. As can be seen from Figure 5 and Table 2, the mean value of RMSSDs of participants on a left turn intersection (Section type T1) is at its lowest, while on non-intersection roads divided by central reservation (Section type T8), the mean value of RMSSDs is at its highest. It indicates that a driver's mental workload is at its highest when driving on a left turn intersection, while it is at its lowest on non-intersection roads divided by central reservation.
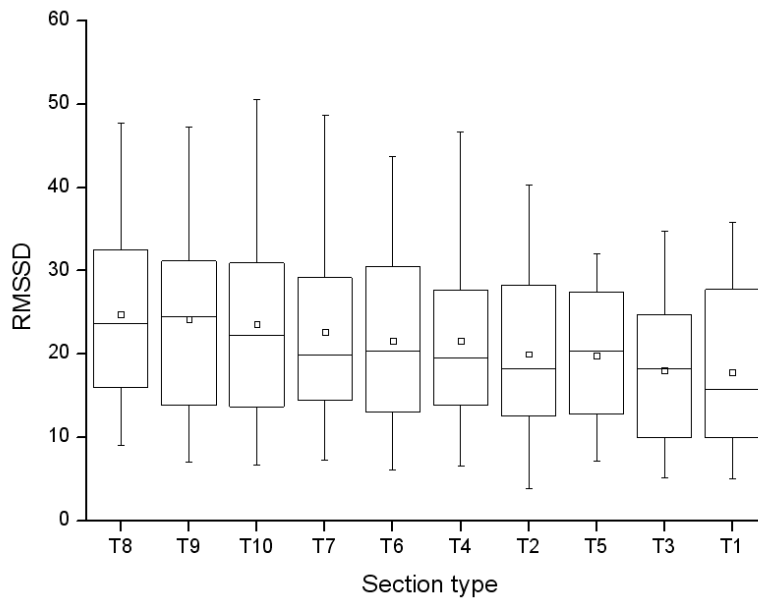

Figure 5   Distribution of participants' RMSSDs on different road types

Table 2   Mean values of RMSSDs on different road types

Section type	Non-intersections				Crossings					
	T8	T9	T10	T7	T6	T4	T2	T5	T3	T1
Mean values of RMSSDs	24.75	24.16	23.62	22.70	21.61	21.60	19.99	19.79	18.04	17.85

Road section types T1-T6 are crossings (intersections and interchanges), and T7-T10 are non-intersections. We carried out t test for the RMSSD data on crossings and non-intersections. The variance of the two populations shows no significant difference ($F = 3.738$, $p = 0.054 > 0.05$), while the mean values of RMSSDs show significant differences ($t = -3.37$, $p = 0.001 < 0.05$). According to the t test results, participants' mental workload when driving on

non-intersections is significantly lower than on intersections. Road section types T1-T3 are intersections and T4-T6 are interchanges. We also carried out t test for the RMSSD data on intersection and interchanges. The result shows that, the two groups show no significant differences when choosing the significance level $\alpha = 0.05$, while they show significant differences when $\alpha = 0.1$ ($t = -1.687$, $p = 0.093$). It indicates that the participants' mental workload was higher when driving on intersections rather than on interchanges. Among the three passing directions on intersections, mental workload of left turn (T1) is at its highest. When comparing section type T7 and T8, we can see that they both have a central reservation but different speed limits (70 km/h for T7 and 40 km/h for T8). The participants' mental workload on the T7 section was higher than on the T8 section, which indicates that high speed can lead to an increase in mental workload.

Effects of Driving Experience on a Driver's Mental Workload

In order to find out whether the mental workload of more experienced drivers is different from that of novice drivers, we compared the mean values of the three HRV indicators of the experienced and novice drivers (see Figure 6).

As can be seen from Figure 6(a), the fluctuating rate of heart rates for novice drivers is slightly higher than that for experienced drivers. The test result shows that $F(1,52) = 15.1849 > 4.0266$, $p = 0.00028$, $\alpha = 0.05$. It indicates that there are significant differences of fluctuating rate of heart rates between the two groups.

It is shown in Figure 6(b) that the novice drivers' RMSSDs are obviously lower than experienced drivers, and the trend is basically the same on the different road segments. The test result for RMSSD show that $F(1,52) = 77.5296 > 4.0266$, $p = 6.96\times10^{-12}$, $\alpha = 0.05$, which indicates a significant difference of RMSSD between experienced drivers and novice drivers.

Researchers have found that, age had an impact on HRV (Stein, Kleiger, & Rottman, 1997; Zhang, 2007) and HR (Mehler, Reimer, & Coughlin, 2010). Generally, older age groups had consistently lower HRV than younger people, and HR was found to increase in a relatively linear manner with workload. Driving leads to a greater mental workload for the older drivers than for the younger drivers and this effect was exacerbated by the more complex driving context (Cantin, Lavalliere, Simoneau, & Teasdale, 2009). In our research, the mean age is 41.1 years old for experienced participants and 33.6 years old for novice participants. When considering the impact of age, we see that the difference between the two groups tends to increase.

The test results for data in Figure 6(c) show that there is no significant difference on LF between experienced and novice groups. Overall, when driving on different road segments, the LFs for experienced drivers are neither much higher nor much lower than those of novice drivers. $F(1,52) = 0.0906 < 4.0266$, $p = 0.7645$, $\alpha = 0.05$.
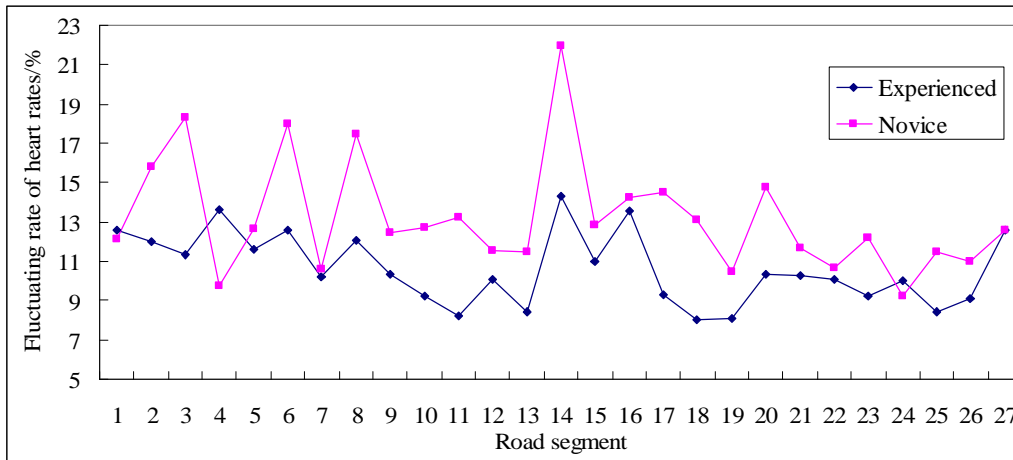
(a) Effect of driving experience on fluctuating rate of heart rates
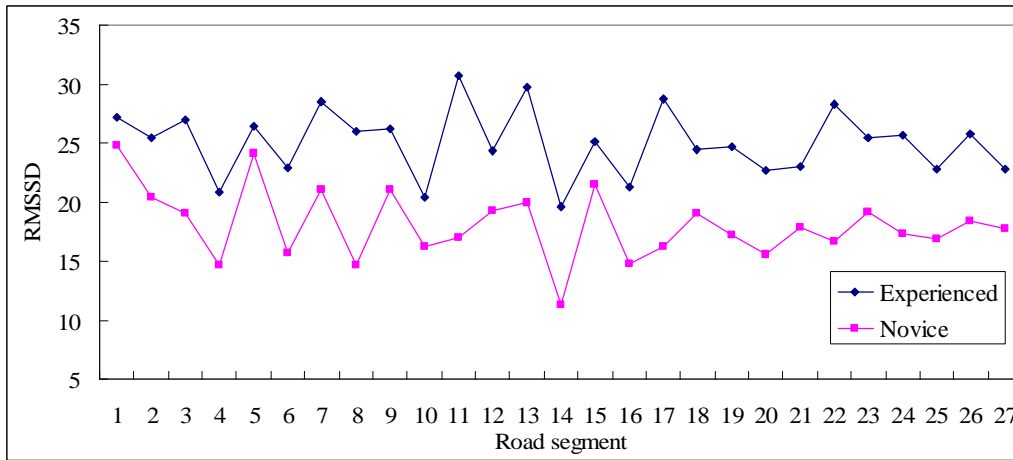
(b) Effect of driving experience on RMSSD
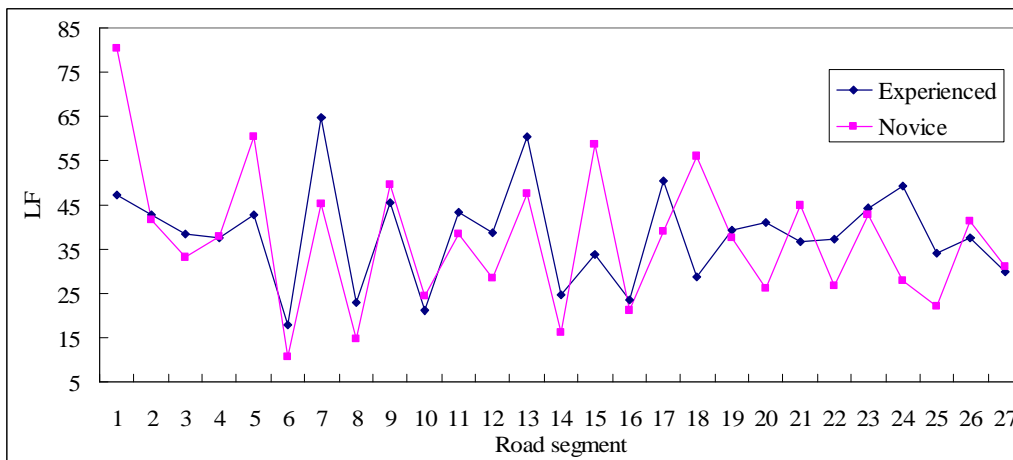
(c) Effect of driving experience on LF

Figure 6   Effects of driving experience on drivers' mental workload

It is indicated from Figure 6(a) and Figure 6(b) that in the same road conditions, the mental workload of the experienced group is less than that of the novice group, that is to say, when driving in the same road conditions, the novice drivers need to use more mental effort than the experienced drivers. In an urban road environment, the fluctuating rate of heart rates and RMSSD can be used to distinguish different driving experience groups, while the value of LF cannot be used to show this difference.

The Correlation between Eye Movement and Electrocardio Indicators

In order to find out whether mental workload has an effect on a driver's eye movement and visual search behavior, we analyzed the correlation between four eye movement readings and three HRV readings.

The correlation between fluctuating rate of heart rates and eye movement indicators (fixation duration, saccade amplitude, average and peak values of saccade velocities) is shown as a scatter plot in Figure 7.
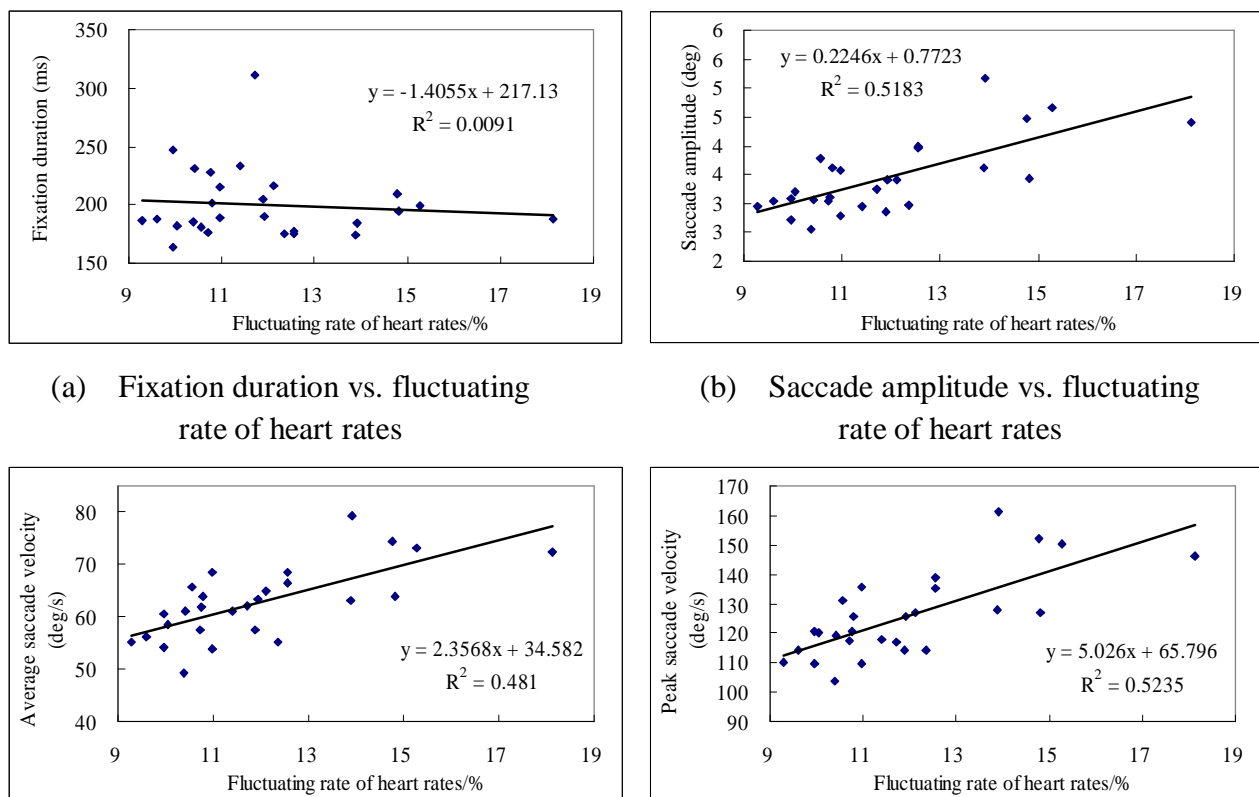

(a) Fixation duration vs. fluctuating rate of heart rates

(b) Saccade amplitude vs. fluctuating rate of heart rates

(c) Average saccade velocity vs. fluctuating rate of heart rates

(d) Peak saccade velocity vs. fluctuating rate of heart rates

Figure 7   Correlation between eye movement parameters and fluctuating rate of heart rates

As shown from Figure 7(a), there is no correlation between fixation duration and fluctuating rate of heart rates. However, in Figure 7(b), Figure 7(c) and Figure 7(d), it is found that there is a positive correlation not only between saccade amplitude and the fluctuating rate of heart rates, but also between saccade velocity (average and peak) and the fluctuating rate of heart rates. As the fluctuating rate of heart rates increases, the three saccade parameters (saccade amplitude, average saccade velocity and peak saccade velocity) tend to increase.

The correlation between RMSSD and eye movement parameters (fixation duration, saccade amplitude, average and peak saccade velocities) is shown as a scatter plot in Figure 8.
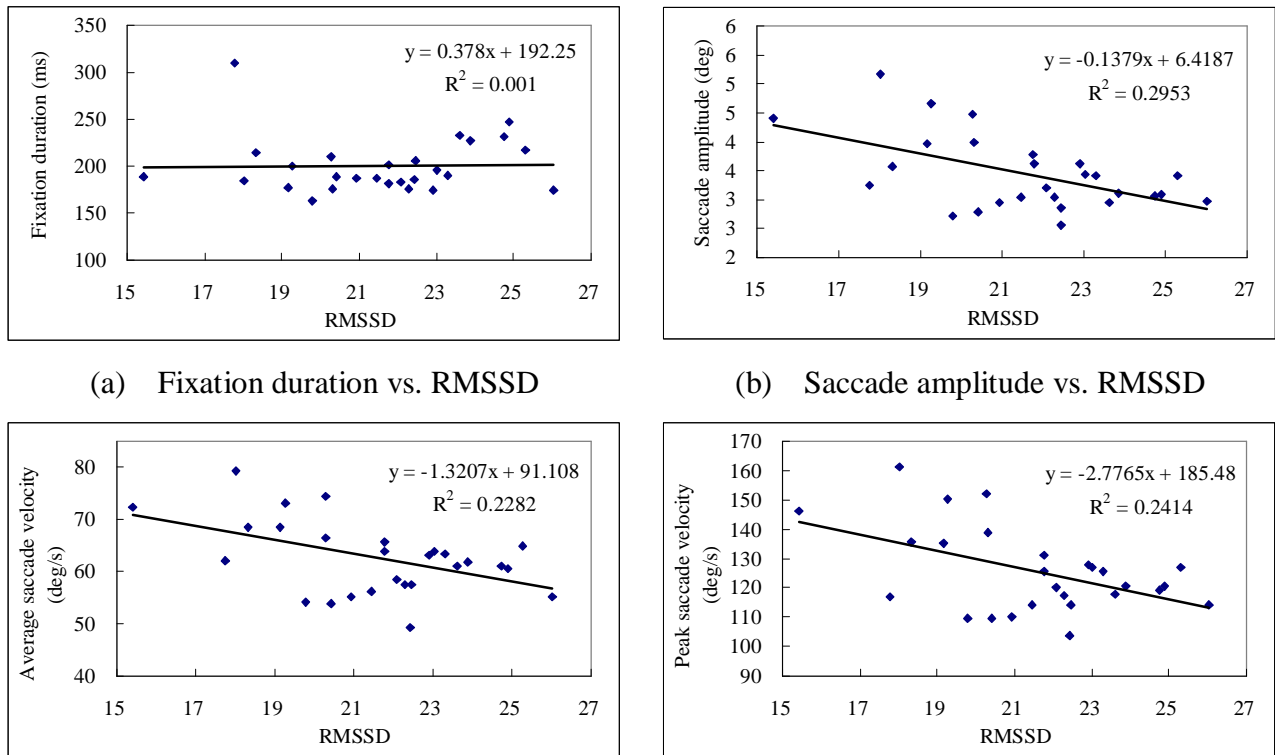
(a)   Fixation duration vs. RMSSD   (b)   Saccade amplitude vs. RMSSD

(c)   Average saccade velocity vs. RMSSD   (d)   Peak saccade velocity vs. RMSSD

Figure 8   Correlation between eye movement parameters and RMSSD

It is shown in Figure 8 that there is no correlation between fixation duration and RMSSD. A weak negative correlation is found between saccade amplitude, saccade velocity (average and peak) and RMSSD. As the value of RMSSD increases, the three saccade parameters (saccade amplitude, average saccade velocity and peak saccade velocity) tend to decrease.

The correlation between LF and eye movement indicators (fixation duration, saccade amplitude, average and peak saccade velocities) is shown as a scatter plot in Figure 9.

According to statistics (Gan, et al., 2005), there is a correlation between two variables if the

correlation coefficient R is larger than 0.5, and there is a strong correlation if R is larger than 0.7. It is shown in Figure 9 that there is no correlation between fixation duration and LF, but there is a negative correlation between saccade amplitude, saccade velocity (average and peak) and LF. As the value of LF increases, the three saccade indicators (saccade amplitude, average saccade velocity and peak saccade velocity) tend to decrease.

(a)   Fixation duration vs. LF   (b)   Saccade amplitude vs. LF

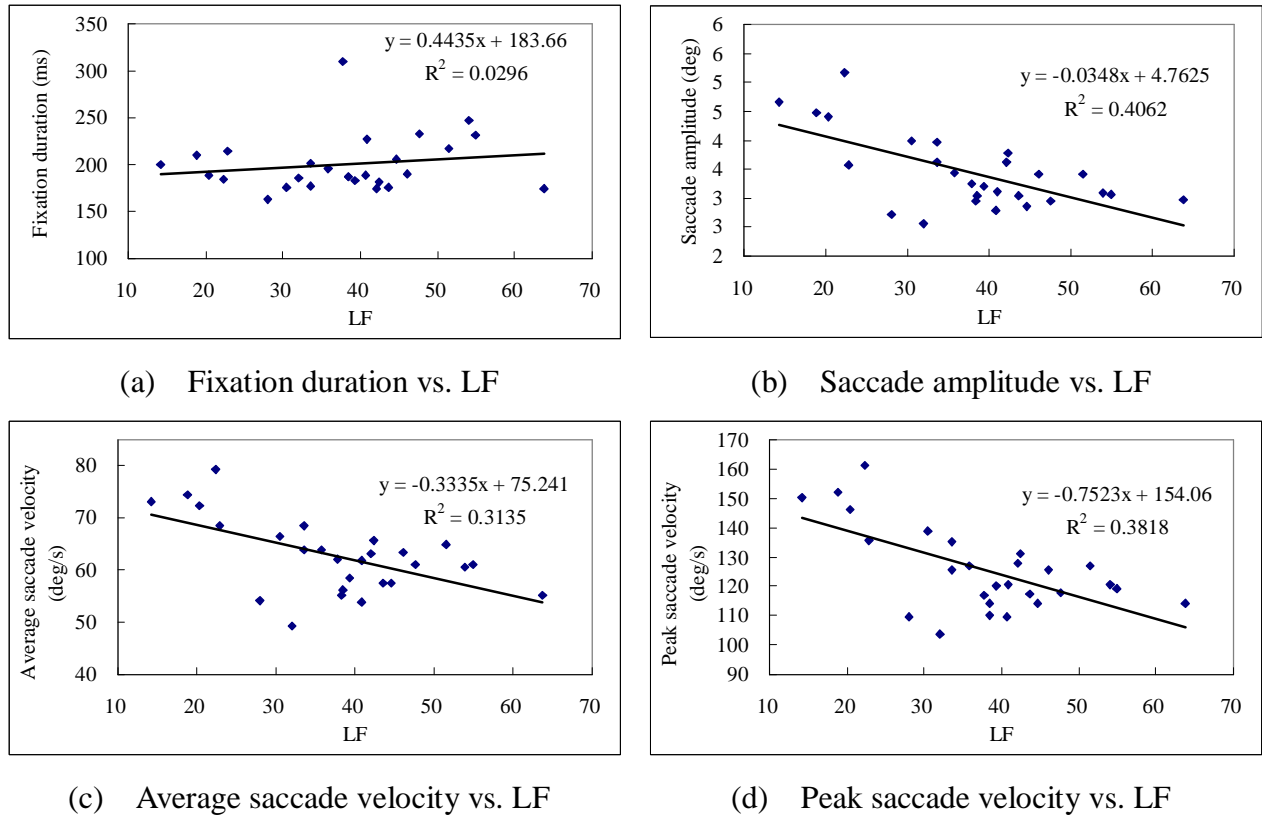(c)   Average saccade velocity vs. LF   (d)   Peak saccade velocity vs. LF

Figure 9   Correlation between eye movement parameters and LF

We carried out the correlation tests on fixation duration and three saccade parameters with fluctuating rate of heart rates, RMSSD, and LF. The results are shown in Table 3.

Table 3   Correlation test results between eye movement parameters and electrocardio indicators

	Saccade amplitude	Average saccade velocity	Peak saccade velocity	Fixation duration
Fluctuating rate of heart rates	0.7199	0.6936	0.7236	-0.096
RMSSD	-0.5434	-0.4777	-0.4913	0.0316
LF	-0.6373	-0.5599	-0.6179	0.1720

Data in Table 3 show:

- A strong positive correlation between saccade amplitude and fluctuating rate of heart rates; a negative correlation between saccade amplitude and RMSSD, and between saccade amplitude and LF;
- A positive correlation between average saccade velocity and fluctuating rate of heart rates; a negative correlation between average saccade velocity and LF;
- A strong positive correlation between peak saccade velocity and fluctuating rate of heart rates; a negative correlation between peak saccade velocity and LF;
- No correlation between fixation duration and the three HRV indicators.

It indicates that mental workload shows little effect on driver's fixation behavior, but it does show a significant effect on saccade behavior. In high mental workload driving tasks, drivers' saccade velocity and amplitude obviously increased.

DISCUSSION

In an urban road environment, there are various road types, such as intersections, interchanges, and non-intersection roadways. The non-intersection roadways have different division forms and different operating speeds and so on. These changes of road environment lead to different demands on drivers. When driving on a road with little interference, for example, on a road with central reservation (Section type T8) at low speed, drivers are able to complete the driving task easily since the driver needs only to observe the vehicles travelling in the same direction. While on complex roads with much interference, such as turning left on intersections (Section type T1), there are many conflict points and the driving task is complex; the drivers need not only to observe the vehicles travelling in the same direction, but also oncoming vehicles and right-turning vehicles. They may also encounter a pedestrian walking through the intersection and non-motor vehicles. The complex driving task will increase pressure on the driver, creating tension. All three of the electrocardio indicators (fluctuating rate of heart rates, RMSSD and LF) show the mental workload differences resulting from different road section types, and these three indicators show consistent results.

Comparison of the fluctuating rate of heart rates and RMSSD for the experienced group and the novice group indicates that to accomplish the same driving task, the novice drivers have to use more mental effort than the experienced drivers. This also partly explains why the novice drivers have a higher accident rate than the experienced drivers. During normal driving, the novice drivers have to use a considerable amount of mental effort to complete driving tasks, so when an unexpected event occurs, the novice drivers do not have enough mental energy to deal with the situation effectively.

As the road environment becomes increasingly complex, the demands on drivers increase. In regard to a driver's visual search behavior, we see that the saccade velocity and saccade amplitude increase. In a complex road environment, drivers need to handle a large amount of information, and focus on more things. They therefore need to improve the search speed and

scope to complete the driving task. It indicates that driving pressure and mental workload come mainly from visual demands, and the visual demand level owing to road environment affects the driving pressure and mental workload.

CONCLUSIONS

In an urban road environment, the driving task demand level varies for different road section types. The fluctuating rate of heart rates, the RMSSD and LF can indicate the effects of certain road section types on mental workload. When driving through an intersection, a driver's mental workload is high and it is higher than passing non-intersection and interchange sections. And when turning left, the mental workload is at its highest. A driver's mental stress is greater when driving through an underpass rather than on an overpass or on the ramp of an interchange. As the HRV indicators, the RMSSD and LF are lower when driving through the underpass of an interchange than when on adjacent sections. In similar road conditions, a driver's mental workload is higher at high speed than at low speed.

When driving on the same road, the mental workload of novice drivers is higher than experienced drivers. The fluctuating rate of heart rates and RMSSD values can reflect the difference between the two groups, while the LF can not reflect the differences between the experienced group and novice group. In the same road conditions, the experienced drivers can more effectively accomplish driving tasks, while the novice drivers need to use more mental effort.

Different section types also affect the driver's visual behavior, primarily affecting the saccade behavior rather than fixation behavior. As the complexity of the road environment increases, a driver's mental workload increases, which leads to an increase in the driver's saccade velocity and saccade amplitude. This indicates that the demands on driving increases due to the road environment and are mainly evident from an increased demand on the driver's visual processes. That is to say, the time for a driver to identify a target is not affected by the complexity of the road environment even if the search target increases and search scope widens in the same time interval.

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