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Research Article

Analysis on the Correlation Degree between the Driver's Reaction Ability and Physiological Parameters

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In this paper, the correlation degree between driver's reaction time and the physiological signal is analyzed. For this purpose, a large number of road experiments are performed using the biopac and the reaction time test systems to collect data. First, the electroencephalograph (EEG) signal is processed by using the fast Fourier and the inverse Fourier transforms. Then, the power spectrum densities (PSD) of α, β, δ, and EEG wave are calculated by Welch procedure. The average power of the power spectrum of α, β, and θ is calculated by the biopac software and two ratio formulas, $(\alpha + \theta)/\beta$ and α/β, are selected to be the impact factors. After that the heart rate and the standard deviation of RR interval are calculated from the electrocardiograph (ECG) signal. Lastly, the correlation degree between the eight impact factors and the reaction time are analyzed based on the grey correlation analysis. The results demonstrate that α/β has the greatest correlation to the reaction time except EEG-PSD. Furthermore, two mathematical models for the reaction time-driving time and the α/β-driving time are developed based on the Gaussian function. These mathematical models are then finally used to establish the functional relation of α/β-the reaction time.

1. Introduction

The ability to control the vehicle that plays extremely important role in emergency and is directly determined by the reaction ability of the driver during driving. The reaction ability of the driver is closely related to the physiological signal. There are many factors that have an effect on the physiological signal, such as the environmental and the psychological factors. The physiological signal will vary if the reaction ability of the driver changes. The reaction ability and the control ability of the vehicle will decrease when the driver is in fatigue which may have an effect on the driving safety. Hence, it is important to research the relation between the physiological parameters and the reaction ability while estimating the driving fatigue.

The grey correlation analysis is widely used to analyze data in social, economic, and ecological systems. Wang et al., Tong and Jin, Ma et al., and Han et al. used the grey correlation approach to analyze the impact factors of regional sustainable development, the influence factors of social level, and the impact factors of cop production, respectively. The parameters that had the largest correlation to social level and cop production were optimized. Then the economic situation or the production was evaluated and predicted by using the grey model [1–4]. In the aspect of transportation, Ji [5] analyzed the impact factors of traffic accidents by using the grey correlation analysis. For driving fatigue estimation, Sahayadhas et al. and Jeong et al. selected electrocardiograph (ECG) to evaluate the driving fatigue [6, 7]. Lal et al. and Yu selected electroencephalograph (EEG) to quantify the driving fatigue and found that the EEG signal has a significant change during the fatigue [8, 9]. Wang et al. and Rashwan et al. combined the EEG with the ECG to evaluate the driving fatigue [10, 11]. Fan et al. recorded the EEG signal and combined self-assessment with the reaction time to verify the induction of mental fatigue. They selected $(\alpha+\theta)/\beta$, α/β, $(\alpha+\theta)/(\alpha+\beta)$, θ/β, and Shannon's entropy to be the characteristic parameters and found that only α/β has an evident change at the end of 60 min driving [12].

In this research, the reaction time is selected as the characteristic parameter to reflect the reaction ability. Three waves, α, β, and δ, are extracted from the EEG signal. The power spectrum density of each wave is calculated. The average power of the power spectrums of three waves, α,

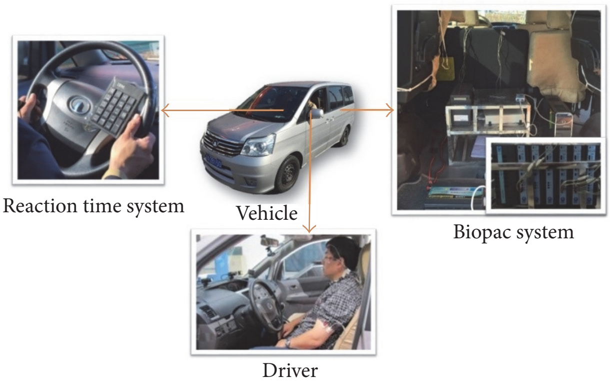


Figure 1: The experimental system.

β, and θ, is calculated by the biopac software and two ratio formulas, $(\alpha + \theta)/\beta$ and α/β, are selected to be the impact factors. Heart rate and the standard deviation of RR interval are extracted from the ECG signal and are also selected to be the impact factors. The grey correlation analysis is then used to determine the impact factor that has the largest correlation to the reaction time. The functional relation between this factor and the reaction time was established.

2. Methodology

2.1. Experiment Design. The experimental system consisted of a multipurpose vehicle, the biopac system, the reaction time test system, and a personal computer system as shown in Figure 1. A multipurpose vehicle was used to provide a driving environment. The biopac system was used to connect to the hardware and also to measure, record, and save the physiological signals during the experiment and to analyze the data afterward. A little keyboard was fixed on the right side of the steering wheel to test the reaction time. The driver's reaction time was recorded and measured by the computer connected to the keyboard and a programming software set.

Fifteen males (75%) and five females (25%) who had driving license and age ranged from 24 to 51 were recruited for the research. In order to ensure the effectiveness of the research, it was made sure that all the participants had no medical contraindications such as disease, alcoholism, drug abuse, and psychological or intellectual problems and they also had good sleep and they had no drinks or coffee 24 hours before the experiments.

Changchun-Hunchun section of G12 freeway was selected as the test road. The speed ranged from 80 to 120 km/h. The average driving time was about 4 hours. The experiment steps are listed as follows.

Step 1. Before the experiment, the driver was familiarized with the devices used for the experiment to avoid the abnormal physiological data and the reaction time.

Step 2. When ready, the driver started to drive on G12 freeway. Tester started the biopac systems and recorded the time. Physiological data were collected in the entire process.

Step 3. During the experiment the tester recorded the driver's reaction time according to the driver's state every three minutes and recorded the data. The reaction time testing method was designed independently to make sure it had no effect on the driving. The method of driver's reaction time test in this research is as follows: computer randomly speaks a number (1, 2, or 3) and the driver is required to press the right button as fast as possible. The period from speaking the number to pressing the button is the considered as the reaction time of the driver and is used to represent driver's reaction ability.

Step 4. After about 4 hours, the biopac system was stopped and the finish time was recorded.

2.2. Signal Processing. Four types of data, EEG, ECG, EOG (Electrooculogram), and the reaction time, were collected from the experiments.

2.2.1. EEG Analysis. The EEG data can be processed by the software in the biopac system. Some EEG recordings include the driver performing various visual tasks such as reading, watching numbers on the keyboard, and reading the guideboard. Under these conditions, the EEG signal might be susceptible to interference from the much stronger EOG signal arising from the eye motion, particularly if EEG signal is recorded from near the front of the skull [13]. Remove EOG Artifacts is used to remove the EOG interference from the EEG signal.

In the electroencephalogram, α wave is in the majority when the driver is relaxed. Beta (β) wave appears when the brain is excited. Theta (θ) and δ waves usually appear when the driver feels fatigue. Hence, the proportion of each wave in the EEG wave can reflect the different fatigue levels. In this research, the EEG signals are divided into 60-second time epochs. The power spectrum densities (PSD) of α (8–13 Hz), β (13–30 Hz), δ (1–4 Hz), and EEG (1–30 Hz) waves are extracted in each epoch. The EEG signal extracted from the biopac system is discrete series. First, the fast Fourier transform is used to transform the EEG signal from time domain to frequency domain using formula (1).

$$x_i = \frac{a_0}{2} + \sum_{k=1}^{m}\left(a_k \cos\frac{2\pi ki}{N} + b_k \sin\frac{2\pi ki}{N}\right), \qquad (1)$$

where $a_0 = (2/N)\sum_{i=0}^{N-1} x_i$, $a_k = (2/N)\sum_{i=0}^{N-1} x_i \cos(2\pi ki/N)$, and $b_k = (2/N)\sum_{i=0}^{N-1} x_i \sin(2\pi ki/N)$, $k = 1, 2, \ldots, m$.

The amplitude of signal can be calculated by formula (2).

$$2\left|c_k\right| = N * \sqrt{a_k^2 + b_k^2}. \qquad (2)$$

The EEG signal is processed by MATLAB. The original and the transformed signals are shown in Figures 2 and 3.

Second, the amplitude of each wave is made equal to zero in the frequency domain. In order to filter the signal, the inverse Fourier transform is used to transform the signal from the frequency domain to the time domain. The time domain signal after filtering is shown in Figure 4.

Third, the PSD of each wave is calculated by Welch PSD. Welch procedure is an improved average periodic diagrams

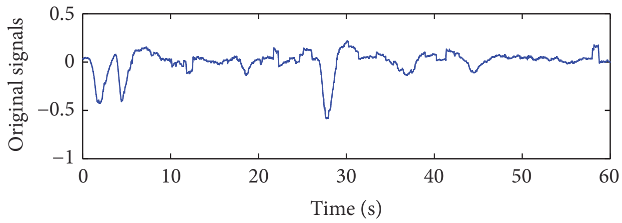


Figure 2: The original signals.

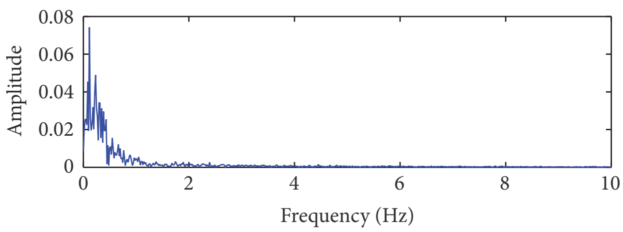


Figure 3: The transformed signals.

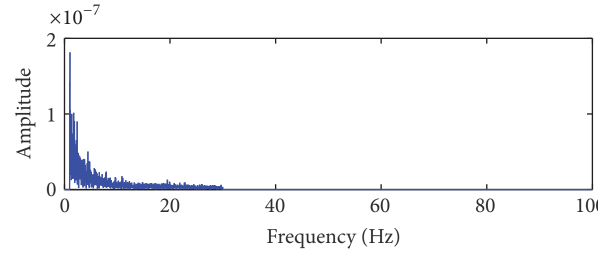


Figure 4: The time domain signal after filtering.

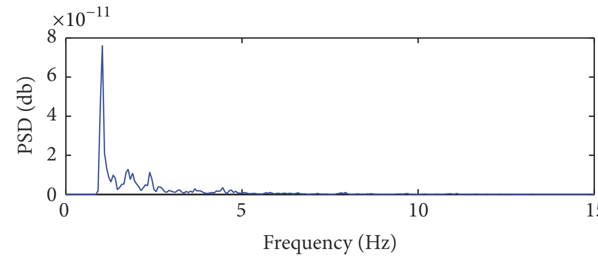


Figure 5: The power spectrum density calculated by Welch.

that can estimate the power spectrum density of random signal. Overlapping segments are allowed when the signal $x_N(n)$ is segmented. The power spectrum density of each segment is calculated by formula (3).

$$\widehat{P}^{i}_{\text{PER}}(\omega) = \frac{1}{MU}\left|\sum_{n=0}^{M-1} x^{i}_{N}(n)\, d_2(n)\, e^{-j\omega n}\right|^2, \tag{3}$$

where $U = (1/M)\sum_{n=0}^{M-1} d_2^2(n)$ is the normalizing factor ensuring that the calculated spectrum is asymptotic and unbiased estimatio, and $d_2(n)$ is adding window function. The power spectrum density estimation of the entire signal is calculated by averaging L segments of periodic diagrams using formula (4).

$$\begin{aligned}\widetilde{P}_{\text{PER}}(\omega) &= \frac{1}{L}\sum_{i=1}^{L}\widehat{P}^{i}_{\text{PER}}(\omega)\\ &= \frac{1}{MUL}\sum_{i=1}^{L}\left|\sum_{n=0}^{M-1} x^{i}_{N}(n)\, d_2(n)\, e^{-j\omega n}\right|^2.\end{aligned} \tag{4}$$

The calculated power spectrum density is shown in Figure 5.

Lastly, the energy of each wave is calculated based on the integral of the power spectrum density. The power spectrum densities of α, β, δ, and EEG waves (represented by α-PSD, β-PSD, δ-PSD, and EEG-PSD) are selected to be the impact factors of the reaction time.

The function *EEG Frequency Analysis* of the biopac system can extract various features from the EEG signal such as α, β, θ, and δ bands. For example, the value of α wave and the average power of the power spectrum are increased when the driver is feeling sleepy. In the biopac system, the average of power spectrum of α, β, and θ waves can be extracted directly. However, there was much interference in the EEG signal, such as the test system itself (change of contact impedance between the electrode plate and the scalp), the alternating current power supply, and the electromagnetic interference [14]. In order to analyze and ensure the reliability of data, Haar wavelet transform is used to eliminate the noise that has changed the α, β, and θ waves intuitively. The average power of the power spectrum of original and transformed α waves is shown in Figure 6.

One wave is unable to represent the driver's state due to other type of interference. Lee et al. discovered that the mutual integration of alpha activity and theta activity produces a more promising effect than alpha or theta activity alone [15]. In this research, two ratio formulas, α/β and $(\alpha+\theta)/\beta$, are also selected to be the impact factors of the reaction time.

2.2.2. ECG Analysis. The motion state of heart, simultaneously controlled by sympathetic and parasympathetic nerves, can be reflected by the ECG signal. The motion state of heart is closely related to the driving fatigue because the sympathetic nerve has direct influence on body's arousal level. Heart rate is a common index of driving fatigue evaluation. Heart Rate Variability (HRV) is the physiological phenomenon of variation between the successive heartbeats that can reflect the automatic nervous system of heart and regulatory function of breath [16]. The HRV is regarded as one of the indexes to evaluate the mental state and can be measured by the variation in the beat-to-beat interval. The statistical indexes of RR interval sequence can evaluate the HRV in time domain (where R is a point corresponding to the peak of the QRS complex of the ECG wave and RR interval is the time between consecutive R peaks in the waveform). One of the statistical indexes is the standard deviation of RR

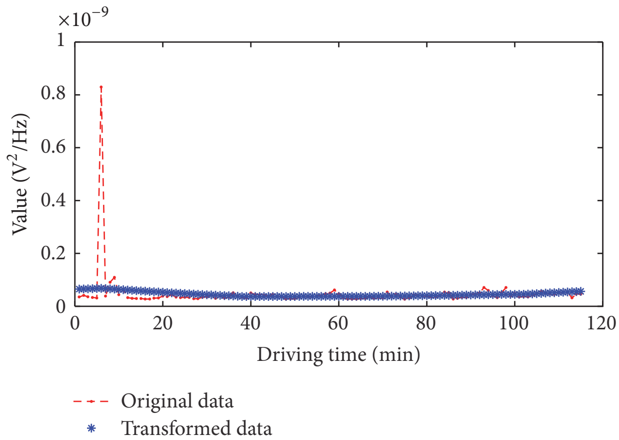


FIGURE 6: Original and transformed data of α wave.

interval (represented by RR_{SD}). The calculation method of RR_{SD} is shown in formula (5).

$$RR_{SD}=\sqrt{\frac{\sum_{i=1}^{N}\left(RR_i-\overline{RR}\right)^2}{N}}. \quad (5)$$

Due to the difference between the origin of heart rhythms, RR_{SD} is changing constantly. The psychological burden of drivers increases when they feel tired, which causes the change of heart rates and RR_{SD}. Hence, heart rate and RR_{SD} are also selected as the impact factors of the reaction time in order to analyze the relation between the ECG signal and the reaction time.

2.3. Grey Correlation Analysis. Partial data of the reaction time and the impact factors are extracted and the trend charts are shown in Figure 7. Both the reaction time and the impact factors have similar varying trends over time. The grey correlation analysis was used to find the impact factor that has the largest correlation with the reaction time.

All of the data is normalized using formula (6).

$$y_i=\frac{x_i-\min_{1\le j\le n}\{x_j\}}{\max_{1\le j\le n}\{x_j\}-\min_{1\le j\le n}\{x_j\}}. \quad (6)$$

The calculation steps of grey correlation analysis are shown as follows.

Step 1. Establish the original matrix x_i of the reaction time, α-PSD, β-PSD, δ-PSD, EEG-PSD, $(\alpha+\theta)/\beta$, α/β, heart rate, and RR_{SD} by formula (7).

$$x_i=\left(x_i(1),x_i(2),\ldots,x_i(k),\ldots\right), \quad (7)$$

where $x_i(k)$ represents the original data of factor i in k minutes.

Step 2. Evaluate the initialization transformed matrix x_i' using formula (8).

$$x_i'=\left(\frac{x_i(1)}{x_i(1)},\frac{x_i(2)}{x_i(1)},\ldots,\frac{x_i(k)}{x_i(1)},\ldots\right)=\left(x_i'(1),x_i'(2),\ldots,x_i'(k),\ldots\right). \quad (8)$$

Step 3. Evaluate the difference sequence $\Delta_{0i}(k)$ using formula (9).

$$\Delta_{0i}(k)=\left|x_0^i(k)-x_0'(k)\right|,$$
$$\Delta_{0i}(k)=\left(\Delta_{0i}(1),\Delta_{0i}(2),\ldots,\Delta_{0i}(k),\ldots\right). \quad (9)$$

Step 4. Calculate the correlation coefficient $\xi_{0i}(k)$ and the grey correlation degree γ_{0i} using formulas (10) and (11).

$$\xi_{0i}(k)=\frac{\min_i\min_k\Delta_{0i}(k)+\varphi\max_i\max_k\Delta_{0i}(k)}{\Delta_{0i}(k)+\varphi\max_i\max_k\Delta_{0i}(k)}, \quad (10)$$

where resolution ratio ($\varphi=0.5$) is used to improve the significance of difference between the correlation coefficients.

$$\gamma_{0i}=\frac{1}{n-1}\sum_{k=1}^{n}\xi_{0i}(k). \quad (11)$$

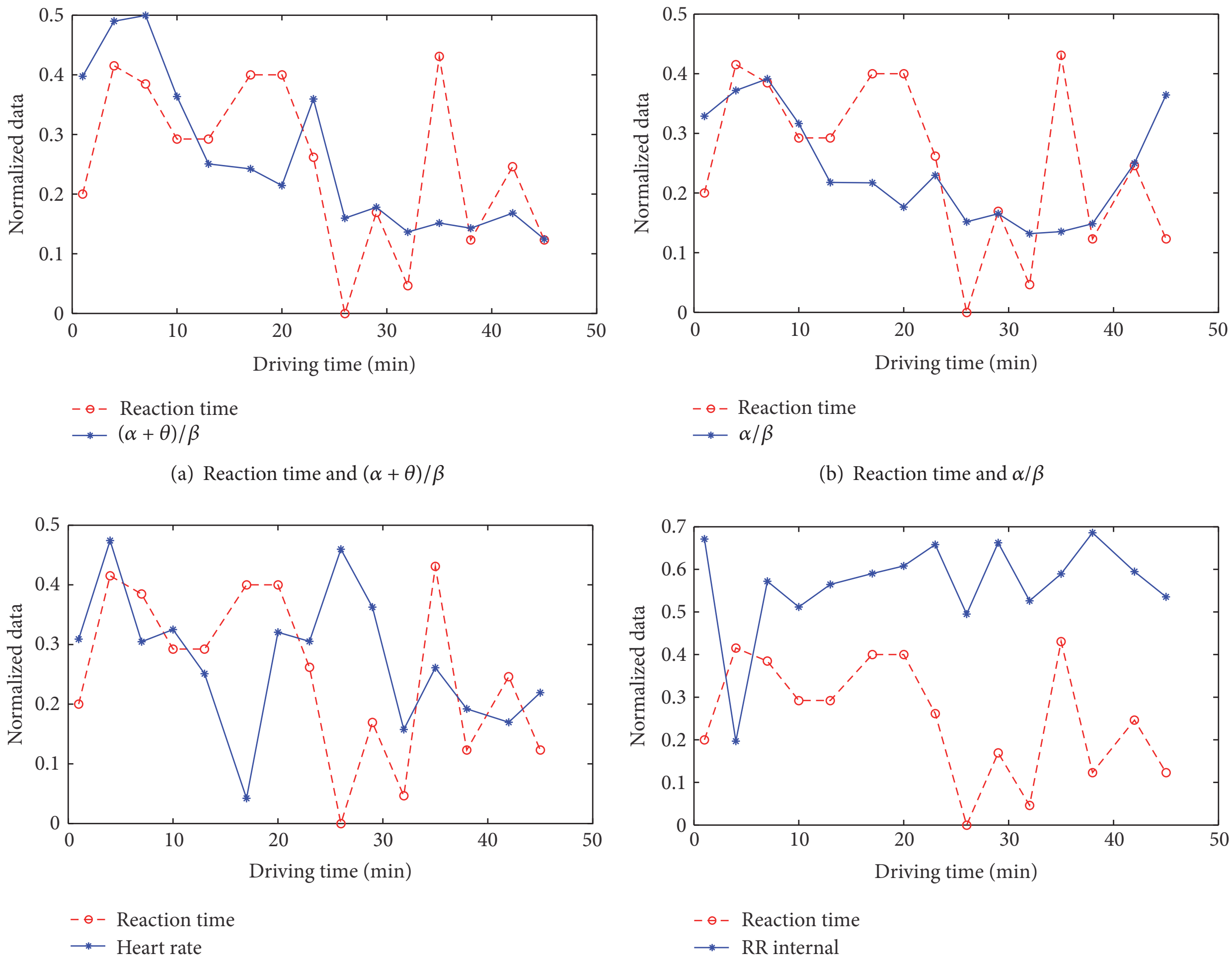
3. Results and Discussion

Twenty groups of data have been analyzed. The results are shown in Table 1.

From the results in Table 1, comparing the eight impact factors, EEG-PSD has the greatest correlation degree (average 0.9712) with the reaction time. The average correlation degree of RR_{SD} calculated from ECG signal is 0.8467. It is obvious that the brain activity has greater influence on the reaction time than the motion of heart. However, EEG-PSD contains all of the frequency of all the waves (1–30 Hz); only several waves are related to mental fatigue. Among the five types of factors extracted and calculated from the EEG signal, α/β has the greatest correlation with the reaction time (average 0.9164).

The mutual integration of α and β waves has a promising effect and it should be analyzed from the frequency domain to the time domain in order to determine the relation between the reaction time, α/β, and the driving fatigue. A 240-minute road test was used to verify the degree of the correlation between α/β and the reaction time. In this road test, the driver experienced a process of being awake to asleep. The reliability of the driver was reflected by the reaction time. The driver became fatigued with accumulation of driving time, which showed distraction and long reaction time. The α wave increased when the driver was sleepy, while β wave appeared if driver was alert. Hence, the value of α/β increased if the driver was in fatigue. First of all, the effect of driving time on the reaction time is observed and it is found that the tendency corresponds to the third Gaussian function. Hence, a mathematical model (the formula (12)) of driving time-the reaction time is established based on the third Gaussian function.

$$y_1=a_1e^{-((t-b_1)/c_1)^2}+a_2e^{-((t-b_2)/c_2)^2}+a_3e^{-((t-b_3)/c_3)^2}, \quad (12)$$



(a) Reaction time and $(\alpha+\theta)/\beta$

(b) Reaction time and α/β

(c) Reaction time and heart rate

(d) Reaction time and RR internal

FIGURE 7: The trend charts of partial impact factors and the reaction time.

where a_i, b_i, and c_i, $(i = 1, 2, 3)$ are the fitting parameters. The mathematical model is fitted by using MATLAB and all of the parameters are calculated.

$$\begin{aligned} a_1 &= 1.889, \\ b_1 &= 474.6, \\ c_1 &= 518.1; \\ a_2 &= 0.1675, \\ b_2 &= 64.93, \\ c_2 &= 63.81; \\ a_3 &= 0.3037, \\ b_3 &= 14.48, \\ c_3 &= 15.42. \end{aligned} \tag{13}$$

So the fitting equation of the reaction time is shown as formula (14).

$$\begin{aligned} T_r = {} & 1.889 \times 10^{14} e^{-((t-474.6)/518.1)^2} \\ & + 0.1675 e^{-((t-64.93)/63.81)^2} \\ & + 0.3037 e^{-((t-14.48)/15.42)^2}, \end{aligned} \tag{14}$$

where T_r is the reaction time and t is the driving time. The coefficient of determination R^2 is 0.8961.

Then, the effect of driving time on α/β is observed and it is found that the tendency corresponds to the second Gaussian function. Hence, a mathematical model (the formula (15)) of driving time-α/β is established based on the second Gaussian function.

$$y_2 = a_1 e^{-((t-b_1)/c_1)^2} + a_2 e^{-((t-b_2)/c_2)^2}, \tag{15}$$

Table 1: The correlation degree between physiological parameters and the reaction time.

Group	α-PSD	β-PSD	δ-PSD	EEG-PSD	$(\alpha+\theta)/\beta$	α/β	Heart rate	RR_{SD}
1	0.7502	0.9260	0.7966	0.9908	0.8325	0.8518	0.7733	0.8646
2	0.7215	0.8810	0.7303	0.9439	0.7693	0.7721	0.7758	0.7488
3	0.8327	0.9873	0.8660	0.8635	0.7983	0.8234	0.9264	0.8947
4	0.6289	0.9132	0.8064	0.9698	0.7103	0.9628	0.7895	0.7633
5	0.7498	0.9586	0.8856	0.9768	0.8176	0.9643	0.8016	0.7645
6	0.7583	0.8207	0.7752	0.9892	0.8223	0.9201	0.7946	0.8625
7	0.9122	0.9304	0.9265	0.9925	0.9246	0.9768	0.9452	0.9413
8	0.7206	0.7932	0.7645	0.9798	0.8758	0.9232	0.8663	0.8297
9	0.8351	0.9608	0.9121	0.9875	0.9466	0.9641	0.9105	0.9354
10	0.8659	0.8541	0.8096	0.9824	0.8012	0.9154	0.7536	0.8356
11	0.8925	0.8193	0.7644	0.9814	0.7813	0.8963	0.7958	0.7924
12	0.8156	0.8566	0.8156	0.9816	0.8021	0.8766	0.6835	0.7804
13	0.8102	0.7654	0.7103	0.9258	0.7179	0.9198	0.7712	0.8509
14	0.7694	0.8189	0.7598	0.9923	0.8045	0.8549	0.8397	0.8264
15	0.7658	0.7120	0.7021	0.9875	0.6998	0.8621	0.8256	0.8433
16	0.7899	0.7822	0.6932	0.9687	0.7431	0.8994	0.7986	0.8157
17	0.8021	0.8879	0.8042	0.9264	0.7612	0.9813	0.7645	0.8296
18	0.8579	0.9543	0.9527	0.9954	0.9011	0.9832	0.9124	0.9254
19	0.8344	0.9653	0.9433	0.9936	0.9348	0.9844	0.9152	0.9168
20	0.8296	0.9678	0.9625	0.9947	0.8812	0.9967	0.9233	0.9124
Average	0.7971	0.8777	0.8190	0.9712	0.8163	0.9164	0.8283	0.8467

where

$$\begin{aligned} a_1 &= 1.234, \\ b_1 &= 260.2, \\ c_1 &= 38.01; \\ a_2 &= 0.7258, \\ b_2 &= 155.7, \\ c_2 &= 166.3. \end{aligned} \tag{16}$$

So the fitting equation of α/β is shown as formula (18).

$$\frac{\alpha}{\beta} = 1.234e^{-((t-260.2)/38.01)^2} + 0.7258e^{-((t-155.7)/166.3)^2}, \tag{17}$$

where t is the driving time. The coefficient of determination R^2 is 0.864.

The new fitting curves are shown in Figure 8.

Figure 8 indicates that the reaction time does not have a positive correlation with α/β all the time, especially during the initial period. During the initial period (0–44 minutes), the driver just began to drive and was unfamiliar to the driving environment during this period. The reaction time initially increased, then briefly decreased, and then increased again during the initial period. Due to the degree of familiarity to the driving environment depending on the driver himself, the driver was in an unstable state at the beginning, which resulted in a high value of reaction time. The reaction time decreased after 23 minutes indicating that the driver had become familiar to the driving task and the test of the reaction time. Hence, the measured reaction time after 23 minutes could reflect the reality of mental state. The reaction time was in the lowest value at the 44th minute then increased gradually. During the stable period (45–188 minutes), the growth rate α/β increased with the same pace as in the initial period, then became slow for a while, and finally reached a relatively stable value. During this period the tendency of the reaction time increased rapidly at the beginning then deaccelerated and its volatility (0.0065) was smaller than before (0.0068), which indicated that the driver was in a stable state. In this period, the state for drive was the finest because the driver had adapted to the environment and his reliability was the highest. The fatigue degree of the driver increased with the driving time accumulation. The driver felt sleepy and

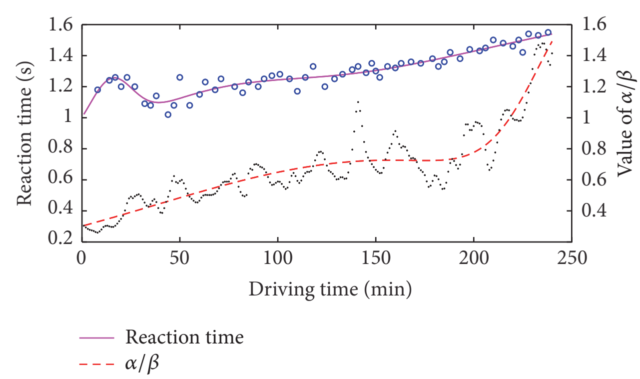


Figure 8: The fitting curves of driving time-the reaction time and driving time-α/β.

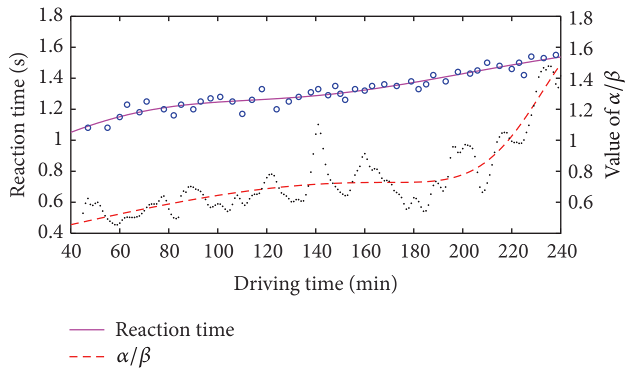


Figure 9: The updated fitting curves of driving time-the reaction time and driving time-α/β.

lost interest in being awaked. The value of α/β rose with an astonishing speed after 188 minutes. The reaction time also increased more quickly than before. The driver was in fatigue and his reliability was low resulting in declined control of the vehicle. It was not appropriate to continue driving during this period [17].

In order to construct the function of the reaction time-α/β, the outliers should be eliminated. The main focus of the research is to analyze the relation between the reaction time and α/β after entering the stable period. The initial period cannot reflect the real state of the driver based on the above-mentioned analysis, so the measured reaction times during the initial period are eliminated. Moreover, the measured reaction time at the 50th minute is also eliminated because the driver was overtaking at that time. The fitting equations (14) and (17) should be corrected after elimination. The observation of the effect of the driving time on the updated reaction time demonstrates that the tendency corresponds to the second Gaussian function. Hence, the new fitting equation of the reaction time is shown as formula (18).

$$T_r = 1.649e^{-((t-329)/334.3)^2} + 0.2887e^{-((t-59.35)/74.5)^2}, \quad (18)$$

where T_r and t are the reaction and driving times, respectively. The coefficient of determination R^2 is 0.9096.

The observed effect of the driving time on the updated α/β shows that the tendency still corresponds to the second Gaussian function. Hence, the new fitting equation of α/β is shown as formula (19).

$$\frac{\alpha}{\beta} = 1.147e^{-((t-258)/35.87)^2} + 0.7265e^{-((t-161.9)/178.3)^2}, \quad (19)$$

where t is the driving time. The coefficient of determination R^2 is 0.8106.

The updated fitting curves are shown in Figure 9.

The relation between α/β and the reaction time is calculated by the elimination method based on equations (18) and (19). The simplified equation of α/β-the reaction time is shown as formula (20).

$$\frac{\alpha}{\beta} = 0.2088T_r + 1.0774\sqrt{T_r + 0.788} + 1.7149, \quad (20)$$

where T_r is the reaction time.

4. Conclusion

In this research, a new method of on-line reaction time measurement has been developed. The EEG signal is processed by using fast Fourier and inverse Fourier transforms. The Welch procedure is utilized to calculate the PSD of α, β, δ, and the EEG. The averages of power spectrum of α, β, and θ waves are extracted from the EEG signal. Heart rate and the standard deviation of RR interval that can represent the HRV are extracted from the ECG signal. Total of eight factors are selected to be the impact factors of the reaction time. These factors are α-PSD, β-PSD, δ-PSD, EEG-PSD, $(\alpha+\theta)/\beta$, α/β, heart rate, and RR_{SD}. The grey correlation analysis is used to distinguish the difference degree between the factors from the microscopic view, which can reflect the relation between the eight impact factors and the reaction time. The results have shown that α/β has the largest correlation with the reaction time. Furthermore, the relation among α/β, the reaction time, and the driving time is analyzed in the time domain. The reaction time and α/β are fitted using the Gaussian function. The fitting curve of the reaction time increased with the driving time after getting into the stable period. The value of α/β has remained low during the initial and the stable periods but has a sharp increase during the fatigue period. The functional relation of α/β-the reaction time is established. The presented research work is potentially applicable in actual drive. The value of α/β can be calculated after measuring the reaction time and then the state of driver can be estimated for further analysis.

Competing Interests

The authors declare no conflict of interests.

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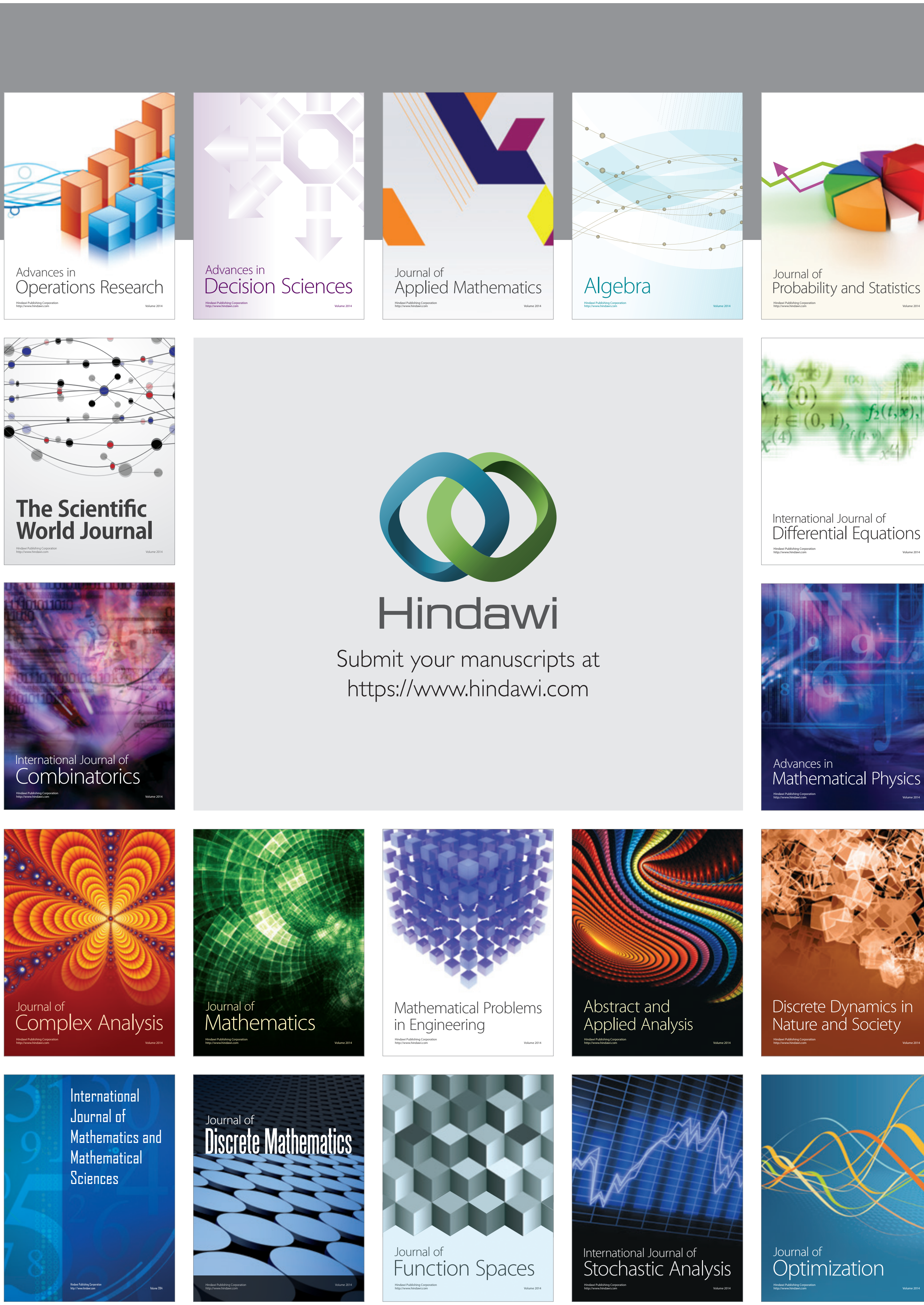
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