# An Analysis of Ear Plethysmogram for Evaluation of Driver's Mental Workload Level

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**Abstract.** Distracted driving has emerged as a factor of road accidents. Usage of cellular phones or car navigation systems has aggravated the problem. Therefore, the detection increase of drivers' mental workload has been a vital issue for establishing safety support systems. Studies on the estimation of driver's mental workload have been performed using a various devices. However, an applicable and a sensitive device is still vague. The purpose of this study is to develop a method to estimate driver`s mental workload level through blood pulse wave analysis. In order to find a standard value that indicates high mental workload, two ways of analyzing pulse wave data have been studied: (1) Average Maximum Lyapunov exponent and (2) Normalized Maximum Lyapunov exponent. The result shows that, the analysis of average a Maximum Lyapunov exponent shows a significant different between the days with a secondary task and the days without the task.

**Keywords:** Mental workload · Plethysmogram · Safety · Driver assistance

## 1 Introduction

A comprehensive accident data in Japan recorded the number of road traffic crashes for the year 2013 reported a decrease of 5.4 % compared to in 2012 [1]. When looking for causes of the crashes, distracted driving, which includes 'looking elsewhere' and 'thinking of something', was 24.8 % of traffic crashes in 2013 [1]. It shows that distracted driving is an important issue to be solved in order to reduce the number of road accident fatalities. Aggravating the problem, various devices, such as mobile phones and car navigation systems used in vehicles, have become a trend nowadays. In addition, there are several studies concluded that the negative effects of using a phone may not result from operating the telephone, but mainly from make a conversation on the phone itself which can relate to 'mental workload' [2, 3].

Currently, the detection of mental workload level has increasingly important especially to develop a caution or warning system. In recent years, researches on state estimation of mental workload have been investigated with various devices. For instance, the study that employed physiological indices such as Electroencephalogram


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(EEG) and Electrocardiogram (ECG) [4–6] can be given. However, it is quite hard to use such indices in an actual driving condition. Consequently a device which can estimate driver's mental workload without giving a driver a sense of restriction is required. Acknowledging the importance to develop a method to detect the driver's mental workload state, plethysmogram which is a device that records blood pulse wave is a promising candidate because it is non-interfere to the driving maneuvers.

There is research that concluded the possibility of using a plethysmogram to quantify the degree of fatigue that results from sitting for extended periods on a driving seats [7]. The usage of a plethysmogram has been expended in driving situation to monitor driver's blood pulse. This device which been located at steering of vehicle were design to predict heart attack while driving [8]. Thus, using plethysmogram is a promising way to monitor driver's condition.

In spite of that, there is still a problem in determining a standard threshold to determine high mental workload state [9]. Hence the goal of this paper is to find a standard threshold of high mental workload which applicable to many drivers.

## 2 Mental Workload and Its Measurement

### 2.1 Model of Mental Workload

The basic concept known about human mental workload is when opposing more mental workload, performance will deteriorate. A model developed by Meister [10] can explain the correlation between mental workload level and task performance. Later, De Waard [11] has further divided the model from three regions into six regions as shown in Fig. 1. As presented in the model, optimum performance is in Region A2. The operator can easily meet the needs of the task demands and achieve a satisfactory level of performance. Whereas the performance in region A1 and the A3 remains unaffected but the operator has undertaken efforts to maintain performance levels. In B region, operators are unlikely to maintain and performance begins to deteriorate. The degradation of performance in B region could be interpreted as the workload is high. While in C region, operator is interpreted as overload and performance at a minimum, while in D region, state of operator is affected [11].

As it is worth to estimate the state before the performance start to deteriorate, this research is particularly interested in the region B, i.e., to find the situation where the mental workload is high and performance start to deteriorate. Ideally when we able to estimate the mental workload region especially on Region B, we can design a support system such as warning system before the performance start to deteriorate.

In driving tasks, the source of driver's workload can be found both inside and outside the vehicle. Model in Fig. 2 could explain the relationship between both inside and outside source driver's mental workload. Both sources could effects driver's performance on the primary task which is safely control on vehicle. The higher demand of the sources to the driver's information processing resource, the effect on the performance of the primary task will be larger.

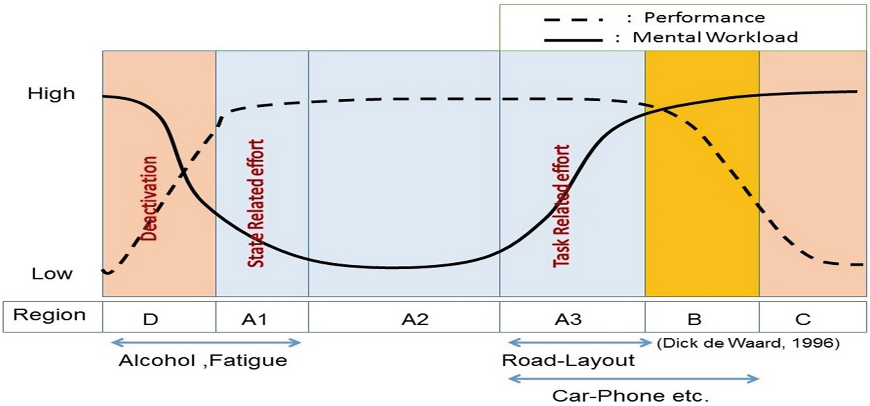


**Fig. 1.** Workload and performance in 6 regions [11]

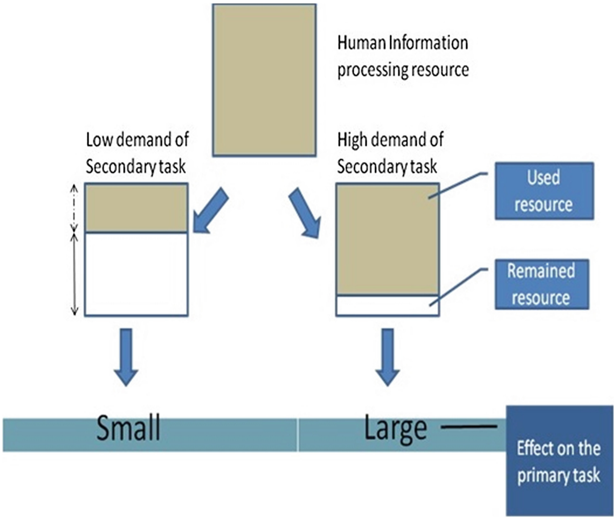


**Fig. 2.** Correlation between primary and secondary task

## 2.2 Measurement of Mental Workload

Measuring mental workload is challenging part of this research. According to O`Donnell & Eggemeier [12] cognitive distraction measurement could be divided into three measurement groups: (1) Physiological measures (2) Subjective measures, (3) Performance measures and. As mentioned previously, this research will focus on physiological measurement as main measurement and compared with other measurement groups. Specifically measuring blood pulse wave of drivers by using a Plethysmogram. Plethysmogram is a device to measure changes in volume of blood or air it contains within an organ or whole body. One of the method to analyse blood pulse wave from plethysmogram is by using maximum Lyapunov exponent. A time series of pulse wave data collected from plethysmogram was first been converted to a 3-dimensional data. Given two points in space, x0 and x0 +Δx0, each will generate its own orbit in space using system of equations. Using an orbit as the reference orbit and orbital separation between the two is also a function of time. Sensitivity to initial conditions can be quantified as ||Δx(t)|| ≈ eλt||Δx0||. If a system is not stable, then the orbit diverge exponentially for a while, but finally settled. Parameter to measure the orbital instability called maximum Lyapunov exponential (λ). More unstable the orbit is higher maximum Lyapunov exponential value will be observed. The maximum Lyapunov exponent of plethysmogram is said to indicate the change of mental workload [9, 13]. The higher the maximum lyapunov exponential mental workload is said to be high [14].

Considering the method to analyze mental workload drivers through maximum Lyapunov exponent, there are two types of analysis is possible. Using (1) raw maximum Lyapunov exponent and (2) normalized Lyapunov exponent. The former is a method by simply taking the mean value of Maximum Lyapunov exponent of all participants in a period of time. This is simple, but there is a concern about the accuracy of the evaluation since this method does not take into account individual differences and internal variability. Suzuki and Okada [14] thus proposed normalizing the maximum Lyapunov exponent based on the reference value determined from the measured data at the early stage of a run. By doing this way, they normalized the value of maximum Lyapunov exponent and get a standard value to all participants. Finally, the value of 120 % is set as a limit. Any value over the limit indicates that the mental workload of the driver is high [14].

This research tried to compare between these two methods of analyzing blood pulse wave and finally attempted to determine the threshold of high mental workload.

## 3 Method

The process of data collection of drivers' mental workload was done using the fixed-base driving simulator. While traffic scenario development and measurement of the movement of vehicles, software produced by Honda Motor was used. Measuring maximum Lyapunov Exponent was done by using plethysmogram's BACS Detector II's from CCI Company.

### 3.1 Participants

There were four males and four females with a mean age of 23.75 and Standard deviation of 5.44 have participated in the data collection process. Every participant holds a valid driver's license and drives almost daily.

### 3.2 Experimental Design

The main task was to drive safely in the left lane. Every participant had two types of traffic conditions, (a) None Hazardous Conditions (NHC) and (b) Hazardous Condition (HC). Under both conditions, participants were also asked to follow a lead vehicle (LV).

Figure 3 describes how the driving task were given to each participant in NHC. A Following Vehicle (FV) was located behind the HV to help participants maintain a following distance. In this traffic condition, FV drove with 65 km/h (constant speed) throughout 7 min trial. Some vehicles also exist in the right lane.

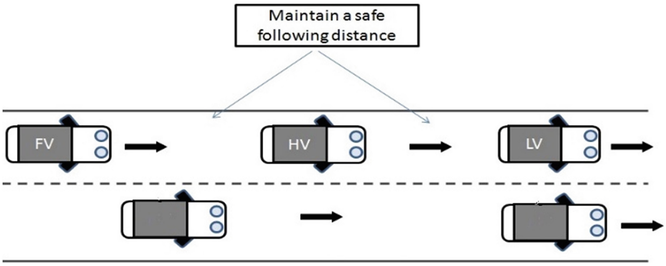


**Fig. 3.** Non hazardous condition (NHC)

While under HC participants were asked to maintain distance between LV and FV. At this time, both LV and FV cruised between speed of 65 km/h and 85 km/h. Intentionally LV and FV will make a sudden brake of 0.35 g and also a quick acceleration. The time to make a sudden brakes and quick acceleration has been set at random (approximately twice the speed changes for each 500 m run). Participants were told to keep a safe following distance and to be alert to sudden changes in the speed of both vehicles (Fig. 4). If they met with a crash during a trial, participants had to start a new trial all over again. This way, participants were tried their best for not involving with a crash.

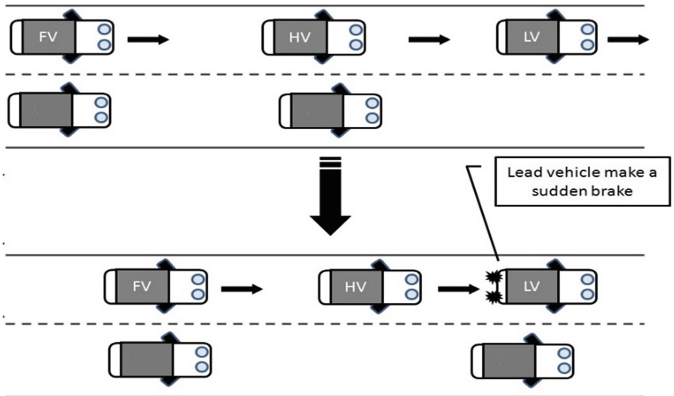


**Fig. 4.** Hazardous condition (HC)

For the secondary task participants were requested to carry out a two-minute Mathematical Arithmetic Task (MAT) in a 7-min run, 3 min after the start and 2 min before the trial is completed (Fig. 5).

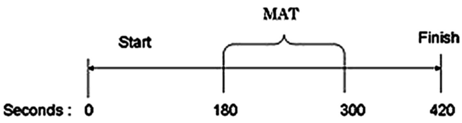


**Fig. 5.** MAT period in a trial

MAT required the participants to memorize the numbers presented before as well as solve the calculation. This is a kind of so-called PASAT (Paced Auditory Serial Addition Test). Arithmetic mathematics task is divided into two levels, namely the level of easy (MAT1) and the level of difficulty (MAT2) tasks. In MAT1, participants were given one-digit numbers (from 1 to 9) in every three seconds through the speakers connected to a computer. Participants had to give answer summation of last two numbers orally as example in Fig. 6. While in MAT2, participants were given two-digit numbers between 11 and 49. As in MAT1, the participants had to answer total of the last two numbers orally.

In each trial, the number of correct answer was calculated and the result was notified to participants after the end of a trial.

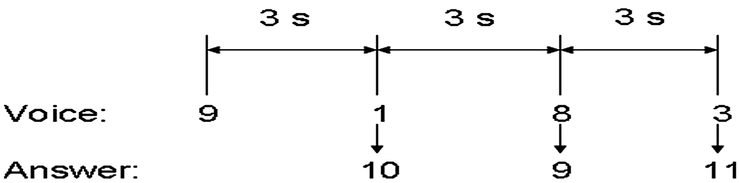


**Fig. 6.** MAT1 (Easy Level)

### 3.3 Procedure

In order to cancel any order effect, all participants were randomly divided into two groups respectively as presented in Table 1. Every participant experienced six days of experiments with six sets of run each day. In the table, BD is the 'Baseline Driving', there was Non Hazardous traffic condition and no secondary task has been opposed to the participants on those days. After completing all trials, participants were asked to answer the questionnaire NASA-TLX as a subjective measurement to estimate the workload in each task.

## 4 Results and Discussion

### 4.1 Raw Maximum Lyapunov Exponent

While performing a mathematical task, we were assumed that demand of mathematical task was remain unchanged during 2 min task. To know the mental workload of participants during the task period, the mean value of maximum Lyapunov exponent for that period has been calculated.

**Table 1.** Experimental procedure

| Group 1 | | Day | Group 2 | |
|---|---|---|---|---|
| Task | Traffic Condition | | Task | Traffic Condition |
| BD | | **One** | BD | |
| MAT1 | NHC | **Two** | MAT2 | HC |
| MAT1 | HC | **Three** | MAT2 | NHC |
| MAT2 | NHC | **Four** | MAT1 | HC |
| MAT2 | HC | **Five** | MAT1 | NHC |
| BD | | **Six** | BD | |

Figure 7 shows an example of raw maximum Lyapunov exponent data of a single run from one of participants. The dotted line is a time between 180 s and 300 s where a period which participants were carrying out Mathematical Arithmetic Task. It should be noted here that, in a single day without secondary task (BD), the mean value of raw maximum Lyapunov exponent has also counted from this time period. After calculating the average maximum Lyapunov exponent for that duration, an average of maximum Lyapunov exponent for the whole day (6 runs overall) has also been calculated.

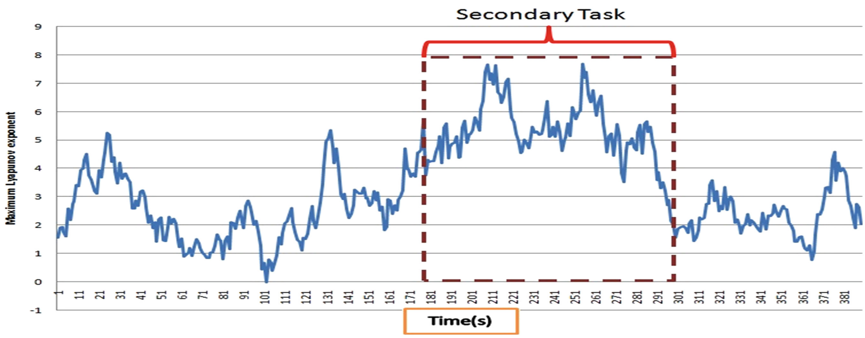


**Fig. 7.** Example of time series maximum Lyapunov exponent data in a trial

Figure 8 shows the mean and standard deviation for maximum Lyapunov exponent between eight participants for each day. The graph shows that the average maximum Lyapunov exponent for the day with secondary task is higher than the days without a secondary task. In fact, according to ANOVA on this data, the main effect of the day is statistically significant ($F(5, 35) = 4.27$, $p < 0.01$). The highest value of average maximum Lyapunov exponent is in the day when participants performed MAT2 under HC. Further Tukey's HSD test indicates that, there is a significant difference when compared MAT2HC with the first day (BD) ($p < 0.01$). This finding is interesting as this correlation is related to the participants performed a difficult level of mathematical arithmetic task (MAT2) while driving in difficult driving condition (HC). A significant difference was also been observed between the first day and MAT2NHC ($p < 0.05$). During this MAT2NHC, the participants had to perform a difficult level of MAT while the driving condition was at an easy level. There was also significant difference between the 1st day and MAT1HC. There was no significant difference between 1st day and MAT1NHC and between the first day and the last day of the experiment.

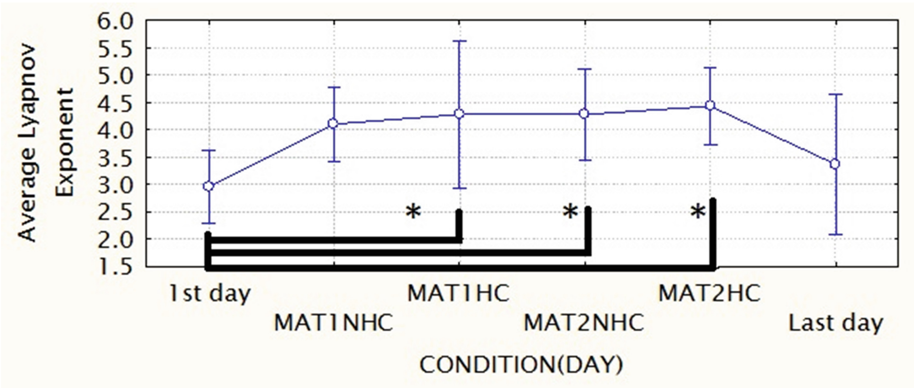


**Fig. 8.** Raw maximum Lyapunov exponent

One of the more significant findings to emerge from this result is that using raw maximum Lyapunov exponent may be acceptable to detect a very high mental workload. However, it would be difficult to distinguish a slightly high mental workload from low mental workload.

### 4.2 Normalized Maximum Lyapunov Exponent

As stated in previous chapter, we also tried to analyze maximum Lyapunov exponent by normalizing it. In this approach, it is necessary to select the "base interval" which is the time period that can be regarded as a mental-workload in low conditions.

Figure 9 shows how to determine the reference in a trial of a participant. The X-axis of the graph is time of a trial in seconds and the Y-axis is the normalized maximum Lyapunov exponent in percentage. The maximum Lyapunov exponent value along the 'base interval' was averaged and was set as 100 %. The maximum Lyapunov exponent is said to be higher than the base interval when the value is higher than 100 %.

Uniqueness of this study exists in the fact that considering that maximum Lyapunov exponent will increase according to the road alignments [9], we select two kinds of time period as a base interval. One is between 45 to 90 s of one trial and another one is between 60 to 180 s. The former base interval is period of run in a straight pathway and no elements that can be considered as the elements of the increasing value of maximum Lyapunov exponent. We set the time period between 60 to 180 s as an alternative of base interval. This interval was selected simply based on the length time is the same with the MAT interval (2 min).

The results of normalized Lyapunov exponent for aforementioned two base intervals were shown in Figs. 10 and 11. Statistical analysis was performed and there was

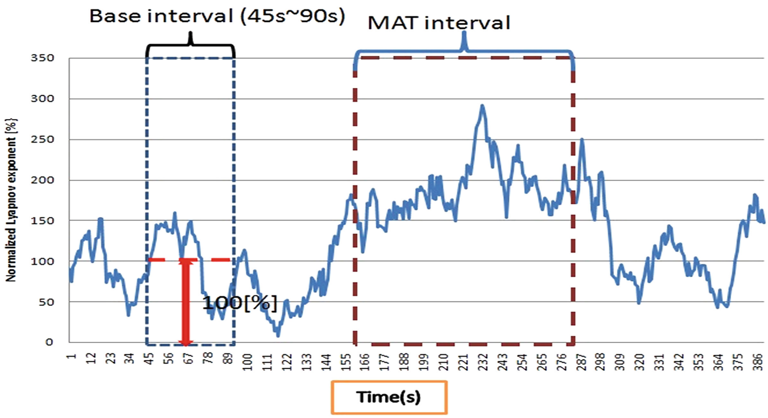


**Fig. 9.** Normalized maximum Lyapunov exponent data for one trial

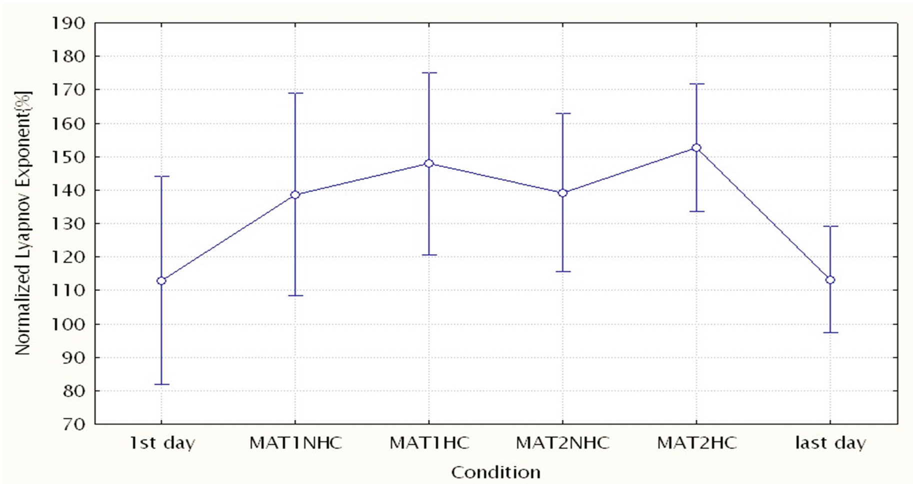


**Fig. 10.** Normalized maximum Lyapunov exponent (45 s-90 s)

no significant difference between these two base intervals. We can infer that further studies are necessary to investigate whether the selection of base interval is really needed or not.

### 4.3 Relationship Between the Subjective Measurement and Maximum Lyapunov Exponent

Figure 12 illustrates relationship between normalized maximum Lyapunov exponents and the subjective measurement of mental workload rated from NASA-TLX. The graph shows that the value of normalized Lyapunov Exponent was high when the task

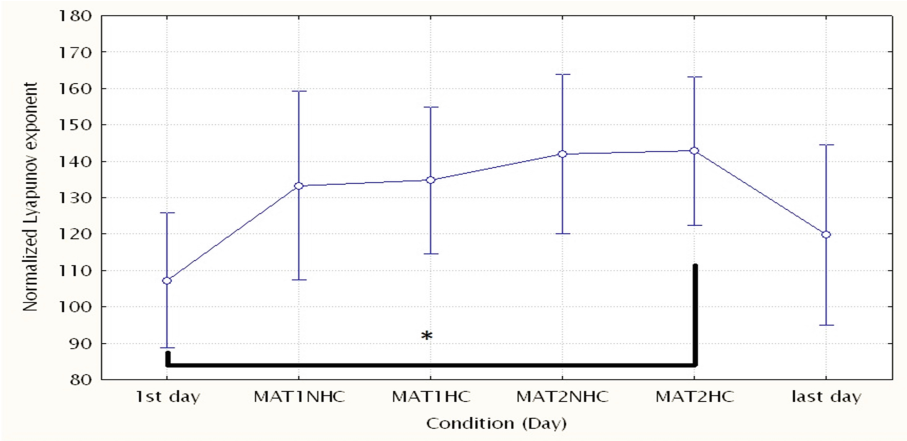


**Fig. 11.** Normalized maximum Lyapunov exponent (60 s-180 s)

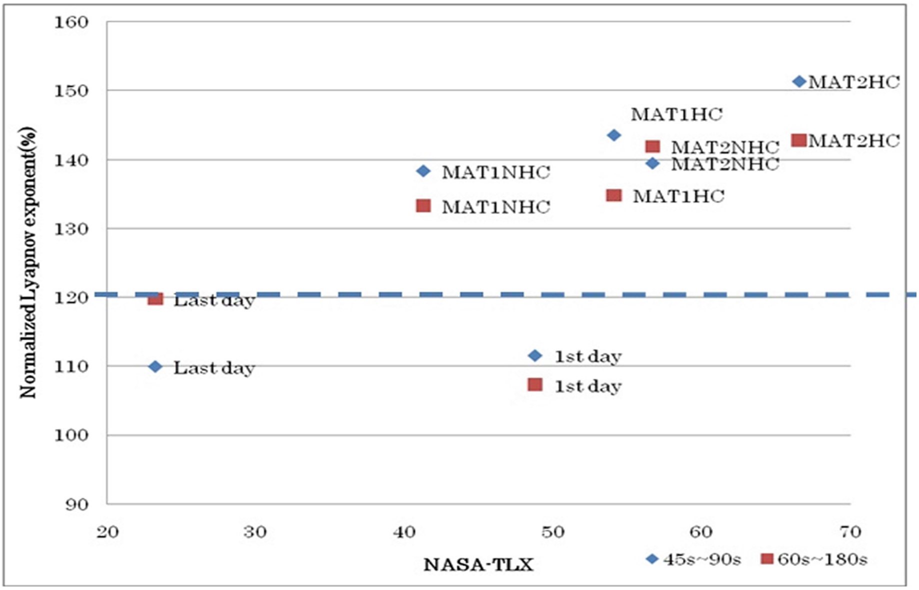


**Fig. 12.** Normalized Maximum Lyapunov exponent and subjective measurement

becoming more difficult. Hence, based on results of our experiment, the value of normalized Lyapunov exponent for normal driving (Baseline driving) is lower than 120 %. The result is in the lines of earlier literature [14] that found value of above 120 % indicates that the driver's mental workload is not in normal driving state in fact in high mental workload.

## 5 Conclusions

The present study was designed to investigate drivers' mental workload by focusing on physiological measurement. An experiment was conducted to gather data regarding driver's mental workload. The main conclusions of this research were as follows:

(1) From raw maximum Lyapunov exponent analysis, using raw maximum Lyapunov exponent may be acceptable to detect a very high mental workload.
(2) Two base interval has been implemented for normalized Maximum Lyapunov exponents. There was no significant difference of selecting the base interval according to the road conditions.
(3) When the value of normalized maximum Lyapunov exponent is 120 % or above, mental workload of drivers is not in ordinary driving state and might be high because of driving task or mental distraction.

## 6 Future Research

This research has thrown up many questions in need of further investigation as follows:

1. Future research on base interval selection may be required.
2. The studies on comparison between the effect of traffic conditions and mathematical arithmetic task on mental workload.
3. Further research on the possibility to distinguish between levels of mental workload.

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## References

1. Japan National Police Agency, Statistics of road Accidents in Japan 2013 (2014)
2. Patten, C.J.D., Kircher, A., Ostlund, J., Nilsson, L.: Using mobile telephones: cognitive workload and attention resource allocation. Accid. Anal. Prev. **36**(3), 341–350 (2004)
3. Patten, C.J.D., Kircher, A., Ostlund, J., Nilsson, L., Svenson, O.: Driver experience and cognitive workload in different traffic environments. Accid. Anal. Prev. **38**(5), 887–894 (2006)
4. C. Ling, H. Goins, a. Ntuen, and R. Li, EEG signal analysis for human workload classification. In: Proceedings. IEEE SoutheastCon 2001 (Cat. No.01CH37208), pp. 123–130 (2001)
5. Sonnleitner, A., Treder, M.S., Simon, M., Willmann, S., Ewald, A., Buchner, A., Schrauf, M.: EEG alpha spindles and prolonged brake reaction times during auditory distraction in an on-road driving study. Accid. Anal. Prev. **62C**, 110–118 (2013)

6. Borghini, G., Astolfi, L., Vecchiato, G., Mattia, D., Babiloni, F.: Measuring neurophysiological signals in aircraft pilots and car drivers for the assessment of mental workload, fatigue and drowsiness. Neurosci. Biobehav. Rev. **44**, 58–75 (2014)
7. Ochiai, N., Yasuda, E., Murata, K., Ueno, Y.: Development of simplified appraisal method of fatigue on sitting for extended periods by the data of finger plethysmogram. Japanese J. Ergon. **40**(5), 254–263 (2004). (In Japanese)
8. Web, T.: Electrocardiogram Check By Car Handle That Predict Heart Attack. Tokyo Shinbun, Tokyo (2013). (In Japanese)
9. Shimizu, T., Miao, T., Shimoyama, O.: Evaluation of Driver's status by Chaotic analysis of finger photoplethysmography, in Technical Report of The Institute of Electronics Information and Communications Engineers, pp. 35–38 (2004) (In Japanese)
10. Meister, D.: Behavioral Analysis and Measurement Methods. Wiley, New York (1985)
11. De Waard, D.: The Measurement of Drivers' Mental Workload. PhD Dissertation (1996)
12. O'Donnel, R.D., Eggemeier, F.T.: Workload assessment methodology. In: Handbook of Perception and Human Performance, Cognitive Processes and Performance, vol II. Wiley, New York (1986)
13. Enokida, S., Kotani, K., Suzuki, S., Asao, T., Ishikawa, T., Ishida, K.: Assessing mental workload of in-vehicle information systems by using physiological metrics. In: Yamamoto, S. (ed.) HCI 2013, Part I. LNCS, vol. 8016, pp. 584–593. Springer, Heidelberg (2013)
14. Suzuki, K., Okada, Y.: Evaluation of driver's mental workload in terms of the fluctuation of finger pulse. Trans. JSME **74**(743), 85–94 (2008). (In Japanese)