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A Novel Physiological Index for Driver's Activation State Derived from Simulated Monotonous Driving Studies

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Abstract: Automobile driving in monotonous situations such as driving for long periods and/or travelling a familiar route may cause the lowering of the driver's awareness level or what we term here as a *Driver's Activation State (DAS)*, resulting in an increased risk of an accident. We propose here to develop means with which to create an in-car environment so as to allow active driving, hopefully thus avoiding potentially dangerous situations. In order ultimately to develop a validated activation method, we firstly set out to examine physiological variables, including cardiovascular parameters, during simulated monotonous driving. Subsequently, we investigated the derivation of a suitable DAS index. During the experiment, a momentary electrical test stimulus of 0.5 s duration was applied at a rate of approximately once per 10 mins to the subject's shoulder to evoke a physiological responses. In 11 healthy male volunteers we successfully monitored physiological variables during the experiment and found particular patterns in the beat-by-beat changes of blood pressure in response to the electrical test stimulus. This finding, explained by autonomic activity balance, suggests that the patterns may be used as an appropriate and practicable index relevant to the Driver's Activation State. (192 words)

Keywords: Automotive safety; Autonomic regulation; Beat-by-beat blood pressure; Cardiovascular monitoring; Driver's activation state; Monotonous driving

Acronyms:

BCR=Baroreceptor Cardiac Reflex

BP=Blood Pressure (SBP=Systolic Blood Pressure, MBP=Mean Blood Pressure, DBP=Diastolic Blood Pressure)

BPRP-ETS=Blood Pressure Response Pattern following the Electrical Test Stimulus

BRS=Baroreceptor Reflex Sensitivity

DAS=Driver's Activation State

DASI= Index of the Driver's Activation State

ECG=Electro-cardiogram

EEG=Electro-encephalogram

EOG=Electro-oculogram

ETS=Electrical Test Stimulus

FPG=finger photo-plethysmograph

MEM=Maximum Entropy Method

NPV=Normalized Pulse Volume

OJL=Objective Judgment Level

1. Introduction

In our highly motorized society the benefits of improved mobility must be seen in context with the social problems arising from the considerable number of deaths and injuries caused by traffic accidents. Clearly, improvements in safety must be desirable and these could possibly be achieved, firstly, through consideration of vehicle features, including the intrinsic safety and reliability of the car itself and, secondly, by means of improvements in driver performance. In the present research we are concerned with the latter area. In this regard it is of utmost importance for a driver to maintain an awareness of factors within their driving environment that are relevant to the task of ensuring safety. This awareness relates to what has previously been defined as 'Situation Awareness' (Endsley, 1995a and b; 2000) which, within the context of automobile driving, implies an ability to perceive, comprehend and correctly interpret relevant factors within the driver's operational environment. This concept has been utilized widely in a number of fields in which decision-making may be influenced by an individual's awareness, such as airplane pilots, medical doctors and soldiers (French et al., 2007; Gaba et al., 1995; Gorman et al., 2006). The term 'Situation Awareness', then, clearly goes beyond the basic understanding of the word 'awareness'. The objective

assessment of awareness is by no means straightforward and methodologies must be developed to fit specific situations. Our interest has been to base a methodology on the measurement of physiological variables, since this can yield objective data. We selected physiological variables that, firstly, were thought to be related to a driver's ability and performance in executing the task of ensuring safe driving and, secondly, could actually be measured reliably and conveniently under real driving conditions.

Having established a strategy for physiological measurement we then introduced the concept of a Driver's Activation State (DAS), which could be derived from such measured data. Thus the DAS would be an objective indication of the state of certain physiological control systems that have relevance to the demands of automobile driving and could therefore be used for driver assessment. Clearly, any measure or index of a driver's activation state should relate in some way to their situation awareness as defined by Endsley, although the exact nature of that relationship will need to be discovered in future studies. An objective measure of the DAS in a driver would thus provide an indication of levels of their awareness, which may then be deemed to be adequate or inadequate to allow safe driving.

We hypothesise here that there exists an appropriate level of the DAS for which the driver may be considered to be capable of achieving safe driving. It is well known that

there are many causes of road traffic accidents, including speeding, drunkenness, and vehicle malfunction. However, we suggest that two of the main causative factors of traffic accidents related to a driver's operational situation are an overload situation (higher DAS) and a monotonous situation (lower DAS). Overload situations include right- or left-turns at busy intersections, travelling at too high a speed, or combinations of several tasks requiring decisions and actions. In order to assist the driver in dealing with such overload situations there have been many technological developments aimed at improving the operational performance of the vehicle such that the risk of a traffic accident may be reduced; examples include Intelligent Speed Adaptation (ISA) (Várhelyi et al., 2001) and Electronic Stability Control (ESC) (Thomas, 2006). In the monotonous situation a driver is under considerably less pressure to make decisions and perform driving tasks. This may arise, for example during regular driving on a daily commuter route, or during long periods of motorway/rural-road travel at constant speed. We hypothesise that during these situations the DAS would be gradually lowered and the driver could have a lapse of attention, resulting in an increased risk of an accident. There are possibly two ways to address the problem of a lowered DAS, which may reduce the risk of a traffic accident, these being:

(A) Development of a Biofeedback System in-car: This system would detect

‘physiological signals’ from a driver, e.g. ECG-RR intervals or blinking etc, that are predictive of lowered-DAS and warn him about possible danger. However, this is a complicated system and many problems need to be solved before a successful practical implementation within a car can be achieved.

(B) Development of a Biofeedforward System in-car: This system would detect ‘monotonous situations’, e.g. driving on a daily commuter route or motorway etc, from a car navigation system and then in some way prevent DAS being reduced to a potentially dangerous level. This is the overall goal of our present study.

In order to realize an advanced in-car Biofeedforward system, it has been necessary to develop a definitive validation method with which to assess practically any potential index of the DAS (DASI). Such validation method would need to be derived and used more conveniently than, for example, that based on the analysis of conventional EEG recordings, which have been widely used as an indication representing brain activity (Åkerstedt and Gillberg, 1990; Horne & Baulk, 2004). We therefore considered, as a first step, the development of a new DASI based on physiological concepts, including the use of cardiovascular parameters that could provide an indirect reflection of brain function (Folkow & Neil, 1971; Fishman & Geiger, 1985). Following this, we propose to develop an activation technique (e.g. acousmatic, vibration, aroma, etc) that could be

validated using the possible DASI during defined monotonous situations. The final goal is, of course, to produce safer driving.

In order to pursue this important objective we firstly acquired several physiological variables, including particular cardiovascular parameters on a beat-by-beat basis, under simulated monotonous driving conditions using a driving simulator. Then, we attempted to derive and evaluate a possible index that could effectively indicate the DAS. We particularly focused our investigation on the beat-by-beat change of cardiovascular parameters in response to the application of a momentary electrical test stimulus (ETS) expecting to see the response of the cardiovascular system to this stimulus during the experiment in order to search for a novel index of the DAS.

2. Materials and Methods

2.1. Experimental System

Figure 1 shows a schematic of the experimental system. It consists of a video projector (LV-5210, Canon Co., Ltd., Japan) and an 80 inch screen for displaying an image to the subject, a driver's seat, two CCD cameras to monitor the subject, a newly developed blood pressure (BP) monitoring system, a finger photo-plethysmograph

(FPG) device, an electrical stimulation device (Low Frequency Treatment Device HV-F05, Omron Co., Ltd., Japan), a multi-telemetry system (WEB-5000, Nihon Kohden Co., Ltd., Japan), and two conventional laptop PCs. To conduct the experiment, the subject is asked to sit down quietly on the seat, with their left hand held horizontally on an armrest at heart level, and to look at the screen as though they were in a car.

The BP monitoring system has been recently developed as an experimental instrument. This system, utilizing the volume-compensation principle, which is capable of measuring instantaneous BP in the finger (Figure 1-(a)), is essentially the same as our previously designed system (Nakagawara and Yamakoshi, 2000). The full details of this are described elsewhere (Nakagawara and Yamakoshi, 2000; Yamakoshi et al., 2000; Yamakoshi, 2003). The finger photo-plethysmograph consists of a near-infrared light-emitting diode (810 nm; L810-40K00, Ebisu Denshi Co., Ltd., Japan) as the light source and a photodiode (HPI-2464R5, Kodenshi Co., Ltd., Japan) as the photo-sensor. They were placed on opposite sides of the distal part of the basal phalanx of the left third finger (Figure 1-(b)). Normalized pulse volume (NPV) was obtained from the DC and AC (pulsatile) components of the photoelectric signal. This measure has been recently proposed as a more valid index of alpha-adrenergic sympathetic activity to the finger arteriolar vessels (Sawada et al., 2001). The seat-pressures of the right- and

left-buttocks as a marker of body movement were measured by two pressure sensors (XFPM-050KPGR-P1, Fujikura Co., Ltd., Japan) connected *via* Teflon-tube of 1 mm inner diameter to 10 mm diameter air chambers placed under the driver's seat (Figure 1-(c)). The ECG measured from chest electrodes, the respiration curve measured with a strain-gauge type pickup sensor (TR-512G, Nihon Kohden Co., Ltd., Japan) wrapped around the subject's chest or abdomen, the C4-EEG according to the Ten-twenty electrode system (Jasper, 1958), and the E1 and E2 EOG as a possible indication of horizontal eye movement, were all collected by the multi-telemetry system (Figure 1-(d), (e)). The electrical test stimulus (ETS) was delivered as a 0.5 s duration pulse of approximately 20.0 V/1.0 mA, but was decided on an individual basis, applied *via* two conducting rubber electrodes attached to the shoulder (Figure 1-(f)). All of the output signals from these devices were stored in one of the laptop PCs *via* a 16-bit A/D converter with 1 ms sampling interval for the purpose of real-time display using LabVIEW 7 Express (National Instruments Co., Ltd., USA).

<Place Fig.1 about here>

2.2. Measurement Quantities

We acquired the following parameters during the experiment: beat-by-beat systolic

(SBP), mean (MBP) and diastolic (DBP) blood pressure in the subject's left forefinger at the proximal phalanx; beat-by-beat normalized pulse volume (NPV); RR intervals from the ECG (RR); seat-pressures of the right- and left-buttocks (Seat Press. Change); respiration waveform (Resp. Curve); respiration rate (Resp) calculated from the peak-to-peak interval of the Resp. Curve; EEG at C4 position (C4-EEG); right-and-left eye movement (E1/E2-EOG).

In this experiment we decided to compare the DAS, as determined from the physiological signals, with some objective indication of the driver's level of drowsiness. This was done from direct observation of the subject and the detection and counting of certain events known to relate to drowsiness. These events detected were: yawn; facial drowsy expression; slow blinking; microsleep judged from body movements; and blinking as monitored by the CCD camera. The event frequency (f_e; number of events/2min) was then used as a reference against which to compare the DAS. Similar methods have been used by Yamamoto (Yamamoto et al., 1994). The derived level of drowsiness is termed the "Objective Judgment Level": "$f_e=0$; wakening [*Level-0* (normal level)]", "$0<f_e \leqq 2$; slightly drowsy [*Level-1* (attention level)]", "$f_e>2$; very drowsy [*Level-2* (danger level)]", and "closed-eyelids more than 10-s; falling into sleep [*Level-3* (serious accident level)]". In addition, the purpose of the EEG and EOG

measurement was only to compare with the OJL reference method.

2.3. Procedures

11 healthy male subjects [33.8 ± 13.9 (SD) yrs] without known cardiovascular disorders participated in the present experiment, after giving informed consent. The subjects were asked to maintain their regular daily routines and sleeping/waking hours from at least 2 days before the experiment took place. They were studied in a quiet and dark room at a temperature of approximately 25°C and requested to sit down in the driving simulator. After giving the subject a mental calculation task in order to activate their brain function for 10 min, the experiment was begun at 9:00 a.m. and carried out in the following order: rest period of 5 min (baseline session); simulated driving period of a maximum 120 min (driving session); rest period of 5 min (end session). During the baseline and end sessions at least one ETS was applied, and during the simulated driving session the ETS was applied at a time decided by the experimenter at a rate of about once per 10 min. As explained above the intention was to use a stimulus that ideally would not be consciously perceived by the subject. The aim of applying the ETS was to see the response of cardiovascular system to a stimulus. In this experiment, two kinds of experimental condition were tested as follows:

Experiment 1: The subjects were exposed to a monotonous screen movie of autonomous travel at constant speed on an oval test-course without any operation. Additionally, in order to simulate a monotonous driving situation, each subject was previously informed that they had to continue watching the movie as if they had actually been driving, and also to refrain from sleeping as far as possible. The termination condition of this simulated driving session was decided by the appearance of *Level-3* in the OJL.

Experiment 2: The subjects were asked to operate a simulator using a steering wheel, accelerator, and brake so as to maintain the speed of 80~120 km/h, and to drive within a specified lane. The termination condition of this simulated driving session was deemed to have been reached either after 120 min or if the vehicle moved out of the specified lane corresponding to what we regarded as extremely low performance (i.e. seriously uncontrolled, resulting from drowsiness).

2.4. Data Analysis

To evaluate circulatory autonomic regulation, the following analyses were made using the collected data of BP & RR. In addition, the EEG and EOG method of data analysis was as described below.

Time-frequency analysis: Spectral analysis was carried out using the BP and RR data by

a maximum entropy method (MEM). It was applied to a data-set of 64 beats, which was updated every 32 beats (moving MEM). The spectral power of systolic BP in the middle-frequency band (0.07-0.14 Hz; PMF(BP)) and of RR in the high-frequency band (0.15-0.4 Hz; PHF(RR)) were calculated. It has been reported that PMF(BP) is expected to be an index of sympathetic activity (Shächinger et al., 2001) and PHF(RR) may be a marker of vagal activity (Pomeranz et al., 1985). Concerning the C4-EEG and E1/E2-EOG data sampled at 200 Hz, analysis was performed on a data-set of 8192 points (= 40.96 s), which was updated every 20.48 s. We derived EEG alpha wave (8-11 Hz) and theta wave (4-7 Hz) power combined (P(α+θ)(EEG)), which is positively associated with increased subjective sleepiness in open eyes condition (Åkerstedt and Gillberg, 1990). Furthermore, we analyzed the slow eye movements (SEMs) recorded by two channels of EOG, by calculating the spectral power of a low-frequency band (0.03-0.1 Hz; PLF(EOG)).

Analysis of baroreceptor cardiac reflex (BCR) function: In order to assess the extent of vagal activity of BP regulation, the baroreceptor cardiac reflex sensitivity (BRS) was derived using Bertinieri's method (Bertinieri et al., 1988): The BCR function is assessed by identifying the spontaneous sequences of three or more consecutive beats, in which SBPs progressively increase (or decrease) and the corresponding RRs progressively

lengthen (or shorten) in a linear fashion ($\gamma^2>0.85$). A regression coefficient or slope (=$\Delta RR/\Delta SBP$) between these consecutive beats of SBP and RR represents a measure of the BRS.

3. **Results**

3.1. Whole Trend-chart

Figures 2 and 3 show typical examples of recordings made in Experiment 1 and 2, respectively. These are the trend-charts of physiological variables together with those of Objective Judgment Level (OJL), normalized NP(α+θ)(EEG) and NPLF(EOG), derived indices of BRS, normalized PMF(BP) (NPMF(BP)) and PHF(RR) (NPHF(RR)), obtained in one subject. The arrows shown along the top of each chart indicate the delivery of the electrical test stimulus, ETS. The spectral power of the EEG and the EOG, NP(α+θ)(EEG) and NPLF(EOG), are shown as the normalized variation from the average value of the baseline session which is calculated as follows:

$$NP(\alpha+\theta)(EEG)=\frac{P(\alpha+\theta)(EEG)-P(\alpha+\theta)(EEG)\big|_{av\_baseline}}{P(\alpha+\theta)(EEG)\big|_{\max}\quad P(\alpha+\theta)(EEG)\big|_{av\_baseline}}$$

where, $NP(\alpha+\theta)(EEG)|_{max}$ is the maximum value in the simulated driving session period and $NP(\alpha+\theta)(EEG)|_{av\_baseline}$ is the average value in the baseline session period.

The spectral powers of SBP and RR are shown as NPMF(BP) and NPHF(RR) which actually represent the normalized variation with respect to each average value derived during the baseline session. The full details of this calculation are described in the Appendix. Less than 1-2 % of the total number of data-sets were classified as artifacts and these were omitted by manual editing.

Examination of Figs 2 and 3 indicates that different patterns of breathing efforts and body movements correspond in some way to the OJL. It can be seen that increases in the frequency of higher respiratory rate (Resp), deep-breathing observed from the respiration curve, and body movements from the seat pressure changes, occurred more often during *Level-1* as compared to *Level-2* (please see the period from 20~40 min in Fig. 2 and from 20~60 min in Fig. 3).

Turning now to the trend-charts of NPMF(BP) and NPHF(RR), it is clearly shown that the sympathetic activity is relatively accelerated (i.e. NPMF(BP)>0) and the vagal activity is suppressed (i.e. NPHF(RR)<0) during the simulated driving session as compared to the baseline session. This tendency was observed in most of the subjects tested. From the recording of the BRS, by taking the reduction of the BCR appearance into consideration, it could be suggested that regulation of BP through a cardiac-related

baroreflex tends to be gradually suppressed in accordance with the gradual lowering of the OJL (*Level-0* → *Level-3*),. With regard to the normalized pulse volume, NPV, as a possible maker of the peripheral sympathetic activity, it is shown that the sympathetic activity (vasomotor constriction) gradually accelerates as compared to that in the baseline session. Consequently, the gradual increase in BP was obtained as a reflection of the acceleration of the sympathetic activity, and this tendency was observed in most of the subjects tested.

<Place Fig.2&3 about here>

These cardiovascular results are statistically proven as below. Figure 4-(a) shows the time course of the means±SDs (n=11) of the percentage change of the MBP, RR, and NPV reactions in the driving session period as compared to the baseline session. Because of the different driving session periods for each subject as shown in Table 1, the horizontal axis is expressed as a %-age of each driving session period (%-driving time). <Place Tab.1 about here> In the right-hand part of Fig.4-(a) are shown the means±SDs of these physiological variables for the whole driving session. Figure 4-(b) shows means±SDs of the sympatho-vagal activity balance (S-V balance) during the driving session analyzed using the NPMF(BP) and NPHF(RR) trend-charts, which is evaluated from the barycentric difference between the baseline and driving session

periods. Additionally, asterisks (*$p<0.05$, **$p<0.01$) indicate the level of statistical significance as obtained by the *Wilcoxon* test.

As shown in Fig.4-(a), it is clearly demonstrated that the BP gradually increases during the simulated driving session of both experiments and this increase is statistically significant ($p<0.01$). Furthermore, taking the statistically significant decrease ($p<0.05$) in NPV into account this increase in BP is likely to have been caused by peripheral vasoconstriction. As shown in Fig.4-(b), this suggestion is also supported by the apparent acceleration of sympathetic activity ($p<0.01$) seen using time-frequency analysis.

<Place Fig.4 about here>

3.2. Physiological Responses to an Electrical Test Stimulus

The arrows shown in the top of Figures 2 and 3 indicate the delivery of the electrical test stimulus (ETS). It can be seen that physiological responses to the ETS were successfully obtained in all the subjects. Of particular note is the finding that the beat-by-beat BP is seen to change in a specific pattern following the ETS in accordance with the subject's activation state. Figure 5 shows typical examples of detailed trend-charts of BP (BP curve), RR and NPV by expanding in time just before and after

the application of the ETS. In Fig.5-(A) and -(B), the indications of ETS-A~-D and –E~-H correspond to those shown at the top of Fig.2 and Fig.3. Also, the BCR sequence in the SBPs and the corresponding RRs appearing in the records is indicated by an elliptical area.

<Place Fig.5 about here>

As shown in Fig.5, there were essentially five types of BP response pattern observed. The first is an increase followed by a decrease in BP [Fig.5-(A)-(a), Fig.5-(B)-(a)], that we term a biphasic response (BR) pattern (i.e., convex <*P*> and then concave curve <P^{-1}> indicated in the BP record). The second is an increase followed by a slight decrease in BP [Fig.5-(A)-(b), Fig.5-(B)-(b)], that we term a slight biphasic response (SBR) pattern. The third is a slight increase in BP [Fig.5-(A)-(c), Fig.5-(B)-(c)], that we term a slight monophasic response (SMR) pattern (i.e., convex curve <*P*>). The fourth is a temporary increase in BP [Fig.5-(A)-(d)] (Fig.5-(A)-(e) shows typical example of another subject), that we term a monophasic response (MR) pattern. The fifth is where there is no significant response in BP, RR and NPV [Fig.5-(A)-(f), Fig.5-(B)-(f)], that we term a non-reactive response (NR) pattern. In all the subjects, these patterns (a)→(e) were usually observed in accordance with a lowering of activation state criteria (*Level-0 ~ -3*). It is noted that in the case of the biphasic response, the RR response to the

momentary stimulation was very similar to that seen in the ‘startle reflex’ reported by Codispoti et al. (2001).

4. Discussion

The study described has attempted to introduce new objective approaches for assessing an automobile driver’s status in so far as it may reflect their physiological potential to drive safely. In order for a driver to be able to control their vehicle safely, making correct decisions when confronted with demanding or hazardous circumstances, and remaining vigilant when taking monotonous journeys, it is generally agreed that they need to be alert. We have introduced the concept of a Driver’s Activation State, DAS, to allow the objective determination from physiological control mechanisms of an indicator of physiological ‘alertness’. Lack of alertness is believed to lead to higher risks of driver error causing an accident. In evaluating what might be considered to be different levels of alertness researchers have used several areas of specialised investigative tools and terminologies, for example those related on the one hand to sleep (Åkerstedt et al., 1990; Horne and Baulk, 2004) and on the other hand to wakefulness (Banks et al., 2005). In our study we have used an indication of the level of drowsiness,

derived from direct observation of body movements and blinking, to produce the "Objective Judgement Level" and this was used as a standard indicator against which to compare any changes seen in the measured physiological variables. In addition, the use of the general concept of 'Situation Awareness' (Endsley, 1995a and b; 2000), recognising as it does the importance not only of the perception of an individual's operational environment but also of the comprehension and correct interpretation of that environment, is clearly of great relevance to automobile driving. It has been suggested that a driver's perception of hazards can be considered as situation awareness and that this is a component of a driver's skill (Horswill & McKenna, 2004).

Our results appear to demonstrate useful relationships between several of the measured physiological variables and the Objective Judgement Level, OJL, and these physiological reactions could be one important aspect reflecting the driver's activation state. We saw increases in the frequency of higher respiratory rate (Resp), deep-breathing, and body movements in OJL-1 as compared to OJL-2. Although subject-to-subject differences make it difficult to draw firm conclusions, from the data shown in Fig. 2 & 3 there appears to be a tendency for these changes to be ranked in the following order: *Level-1>Level-0>Level-2*. This could be explained by considering that the subject would, at least initially, attempt to fight off drowsiness, in other words to

‘activate’ themselves, thereby producing these physiological reactions. It might then be argued that the extended period of driving led to the drivers eventually giving up or being unable to continue to activate themselves. Therefore, if, in an individual driver, this observed response is seen to occur less often, it could be a sign of a potentially dangerous status. This finding suggests that it may be possible to detect potentially dangerous driver status from such breathing and body movement information.

Concerning the cardiovascular parameters, as shown in Fig.4-(a), it is clearly demonstrated that the BP gradually increases during the simulated driving session and this increase is statistically significant ($p<0.01$). Furthermore, taking the statistically significant decrease ($p<0.05$) in NPV into account this increase in BP is likely to have been caused by constrictive peripheral vasomotor regulation. As shown in Fig.4-(b), this suggestion is also supported by acceleration of sympathetic activity ($p<0.01$) using time-frequency analysis. The measurement of this gradual increase in BP during monotonous driving could be useful for assessing one important aspect of a driver’s activation state. It appears that, despite being in monotonous situations, drivers must still face demands, such as ‘to keep an eye on surroundings’ or ‘to shake off their drowsiness’. Although there is not statistical significance between Exp.1 and Exp.2, BP, vasoconstriction observed from NPV and sympathetic activation based on frequency

analysis in Exp.2 appear to be higher than in Exp.1. It is considered that during Exp.2 influences of further stress, such as the need to perform on-going monotonous driving tasks under constrained situations, may be combined. The results obtained here strongly indicate that long hours of driving under such monotonous situations can actually make a driver considerably stressful, resulting in a gradual but significant increase in BP caused by an increase in vasoconstriction through acceleration of sympathetic activity.

Five types of response patterns in BP, as shown in Fig.5, were observed, i.e. biphasic response (BR) pattern, slight biphasic response (SBR) pattern, slight monophasic response (SMR) pattern, monophasic response (MR) pattern, non-reactive response (NR) pattern. These BP responses could be explained on the basis of a balance between vagal and sympathetic activity. As shown, in the biphasic BP response (in Fig.5-(A)-(a), -(A)-(b), -(B)-(a), -(B)-(b)), the decrease in RR would cause the increase in BP (phase $<P>$ region), which means relative suppression of vagal activity, while in the phase $<P^{-1}>$ region the decrease in BP would be due to acceleration of vagal activity, taking the emergence of BCR regulation into consideration. The biphasic response could therefore be explained on the basis of vagal control.

The findings of the monophasic BP responses [Fig.5-(A)-(c), -(A)-(d), -(A)-(e), -(B)-(c)] are strongly suggestive of a degree of low activation state, since these

responses occurred only around the *Level*-2/-3. Although the reason for these responses is at present unclear, it is speculated that, following the stimulation, the vagal activity would be firstly suppressed and then dampening or slowing down in the vagal activity would occur. This would result in only a small decrease in BP, so that there would be no appearance of the $<P^{-1}>$ region, where BP was oppositely raised due to an increase in sympathetic activity, taking the regulation of peripheral vasomotor constriction indicated by the NPV into consideration. On the other hand, the non-reactive BP response [Fig.5-(A)-(f), -(B)-(f)] is an extraneous pattern, which might not be due to autonomic regulation following application of the ETS. This might be considered as a possible 'absent-minded condition'.

Figure 6 schematically shows the criteria for classification of the BP response patterns following the ETS (*BPRP-ETS*). As seen in the upper part of Fig.6, the BP response pattern during the baseline session is set as an individual reference, and the response patterns are then classified into five types compared to the reference as follows: *Stage-BR; -SBR; -SMR; -MR; and –NR*. These are also shown in the lower flowchart. These criteria of the *BPRP-ETS* (BP criteria) were compared with the Activation State criteria, i.e., Objective Judgment Level (OJL), using the test of *Kendall's* rank analysis, the summary of which is shown in Table 2. Significant correlation was obtained

between the BP criteria and the OJL [(a) $r_k=0.763$, $p<0.001$, (b) $r_k=0.747$, $p<0.001$], strongly indicating that *BPRP-ETS* (*Stage-BR, -SBR, -SMR, -MR, and –NR*) could form the basis of a viable physiological index for the DAS. We could therefore define the following levels: *Stage-BR*, Normal level; *Stage-SBR*, Attention level; *Stage-SMR*, Danger level; *Stage-MR*, Serious accident level; *Stage-NR*, Attention or danger level.

<Place Fig.6 about here>

<Place Tab.2 about here>

5. Conclusions

Under laboratory conditions, during the presentation to drivers of either a monotonous screen movie (Exp.1) or a simulation of monotonous driving (Exp.2), we have successfully measured a number of physiological variables and their responses to a momentary electrical test stimulus, ETS, randomly applied to the subject, hypothesising that such responses may be related to the driver's activation state (DAS). It was clearly demonstrated that during the monotonous situation sympathetic activity was increased relatively whilst vagal tone appeared to be suppressed. As a result a gradual rise in BP was observed. Particular patterns of beat-by-beat change in BP in response to the ETS,

which could be explained on the basis of a balance of autonomic activity, were successfully obtained in relationship to the level of the DAS. Although these patterns would appear to be the basis of an appropriate and feasible index of activation state, further experiments under actual driving conditions should be made.

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Appendix

Spectral power of SBP [PMF(BP)] and RR [PHF(RR)] are normalized following steps;

Step1: Both PMF(BP), x, and PHF(RR), y, raw data are assumed to be logarithmic normal distributions. So, firstly we can normalize these so as to obtain geometrical

mean value as “1”, which is given by

$X_i=x_i/g\mu x$

$Y_i=y_i/g\mu y$

where, x_i, y_i: each data, and $g\mu x$, $g\mu y$: geometrical mean value of whole time-series data

Step2: Since X_i and Y_i are still lognormal distribution, we conduct logarithmic transformation. Then, these data are transformed normal distribution so as to give mode value as “0”, which is represented as N(μ-average, σ^2-variance)=N(0, σ^2).

$X_i'=\ln(x_i/g\mu x)$

$Y_i'=\ln(y_i/g\mu y)$

Step3: Dividing Xi’ and Yi’ by each variance value, then we can obtain a standardized form of normal distribution as N(0, 1).

$X_i''=X_i'/\sigma X'$

$Y_i''=Y_i'/\sigma Y'$

where, $\sigma X_i'$, $\sigma Y_i'$: variance value of X_i' and Y_i'

Step4: If we move the median point of X_i'' and Y_i'' in parallel so as to give the baseline value as “0”, we can finally obtain the normalized PMF(BP) [NPMF(BP)] and PHF(RR) [NPHF(RR)], which distribution is expressed as N(baseline, 1).

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Figure captions:

Figure 1 Outline of experimental setup for physiological measurements during simulated monotonous driving. See text for explanation.

Figure 2 Result of Experiment 1: Typical example of 100-min trend-charts of physiological variables together with those of OJL, NP(α+θ)(EEG), NPLF(EOG), BRS, NPMF(BP) and NPHF(RR) obtained in one subject. See text for symbols and explanation.

Figure 3 Result of Experiment 2: Typical example of 90-min trend-charts of physiological variables together with those of OJL, NP(α+θ)(EEG), NPLF(EOG), BRS, NPMF(BP) and NPHF(RR) obtained in the same subject as in Fig. 2.

Figure 4 (a) Means±SDs of time course percent changes from baseline session in hemodynamic reactions to monotonous driving situation. Right bars indicate means±SDs of average value during simulated driving session. (b) Means±SDs of the sympatho-vagal activity balance (S-V balance) during the driving session analyzed by the NPMF(BP) & NPHF(RR) trend-charts. Asterisks indicate significant deviation according to the Wilcoxon test (*$p<0.05$, **$p<0.01$). See text for details.

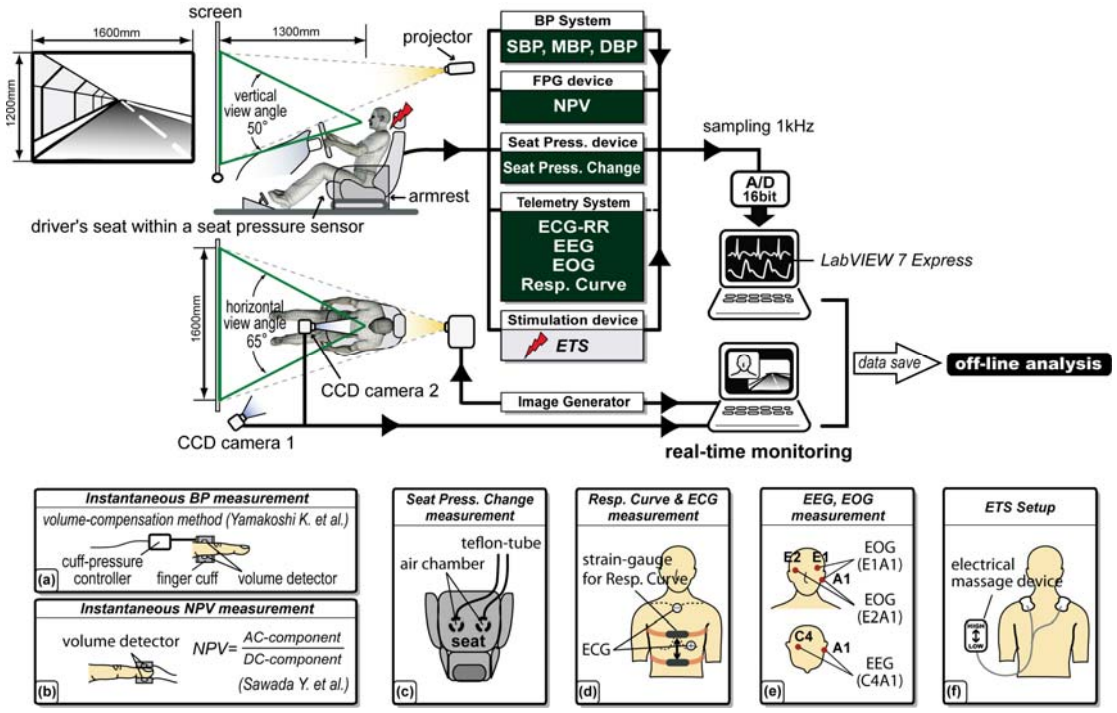
Figure 5 Typical examples of detailed trend-charts of BP, RR and NPV by expanding in time just before and after the electrical test stimulus (ETS). Situations A-D and E-H correspond to those symbols inserted in the top of Fig. 2 and 3. The BCR sequence in the SBPs and the corresponding RRs appearing in the records is indicated by an elliptical area. See text for further explanation.

Figure 6 Schematic criteria for classification of BP response patterns following ETS (*BPRP-ETS*). See text for explanation.

Table captions:

Table 1　Experimental time of Experiment 1 and Experiment2.

Table 2　Frequency distribution between activation state criteria (*Level-0 ~ -3*) and BPRP-ETS (*Stage-BR, -SBR, -SMR, -MR, and -NR*).



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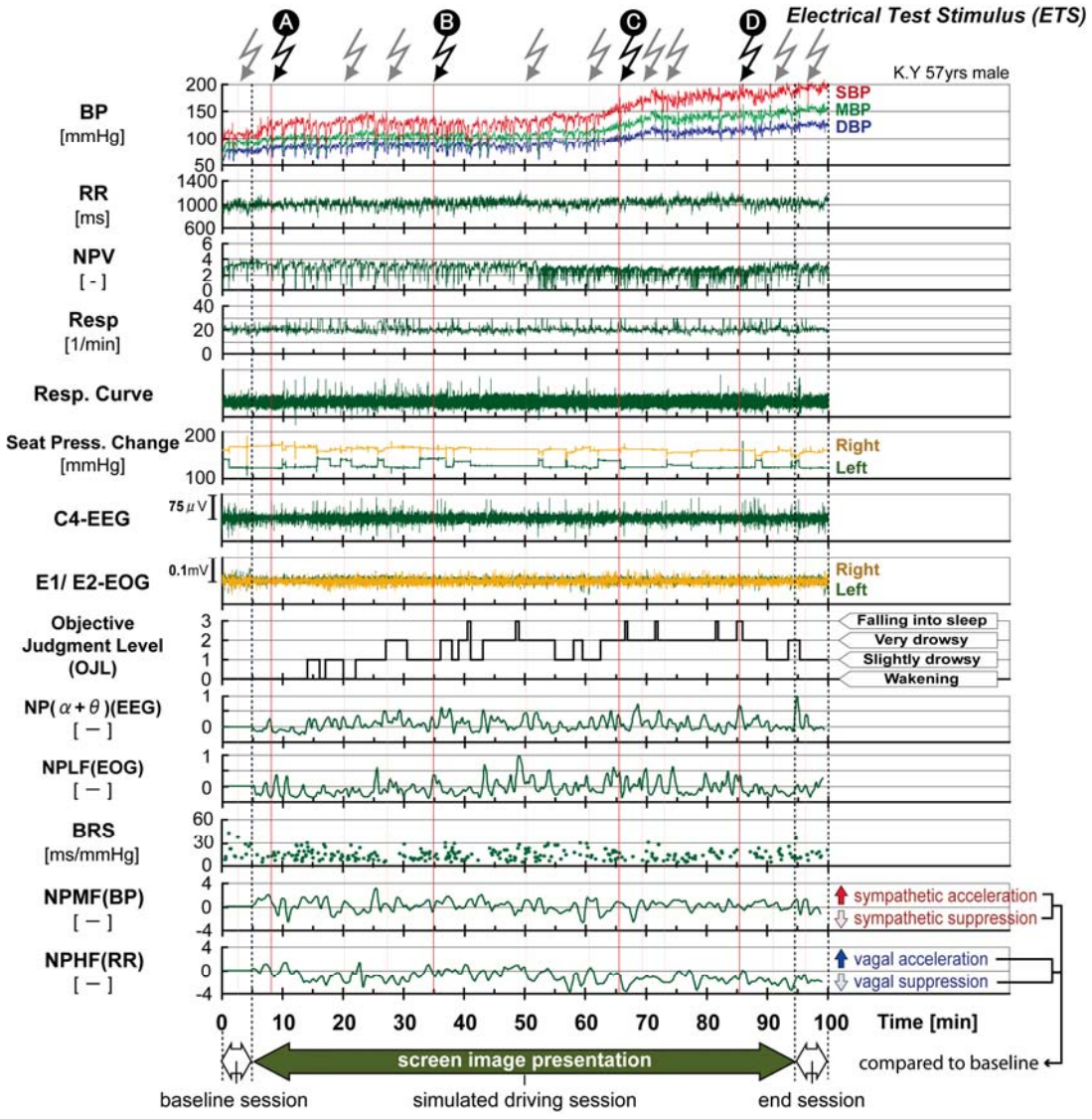

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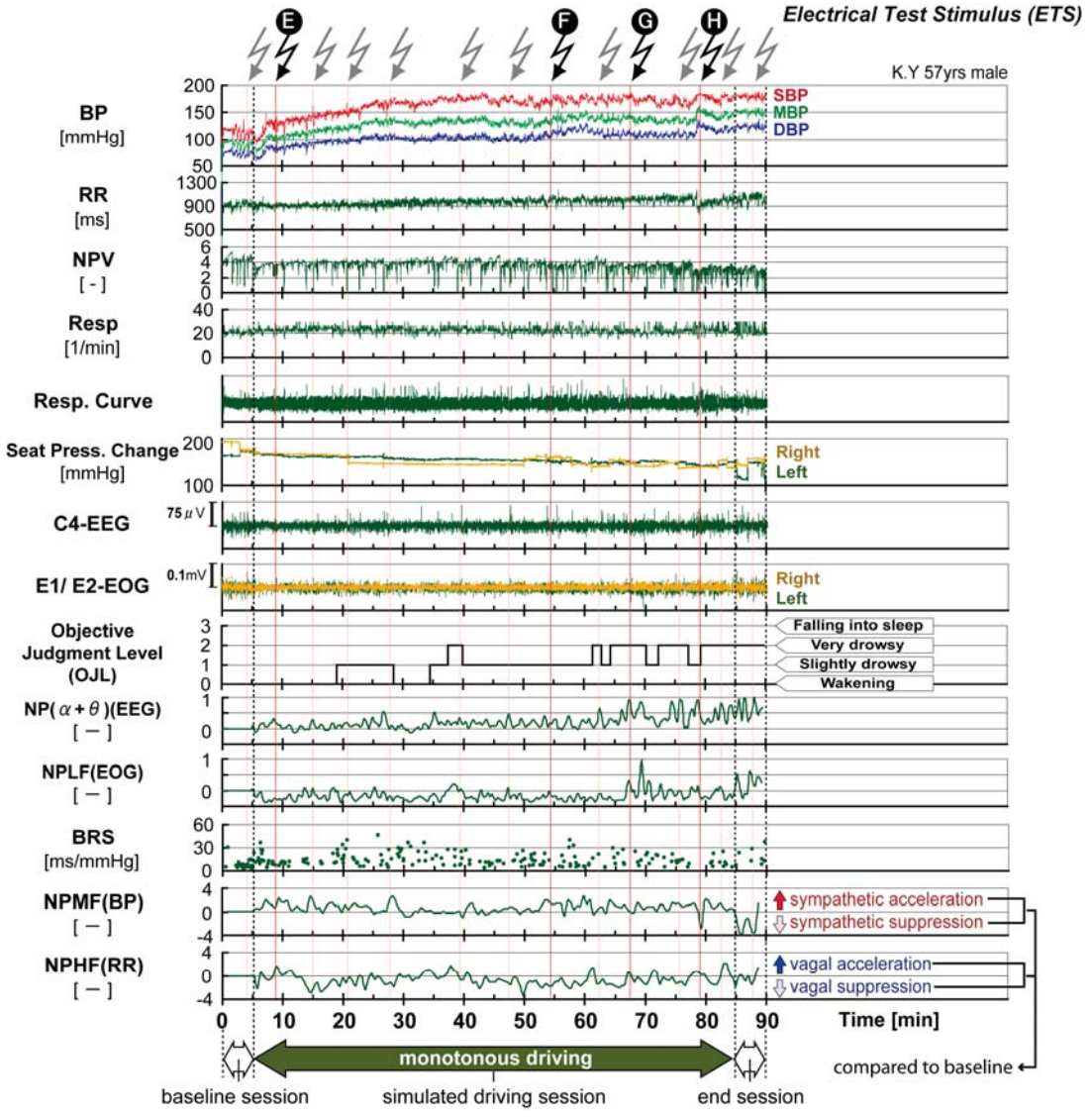

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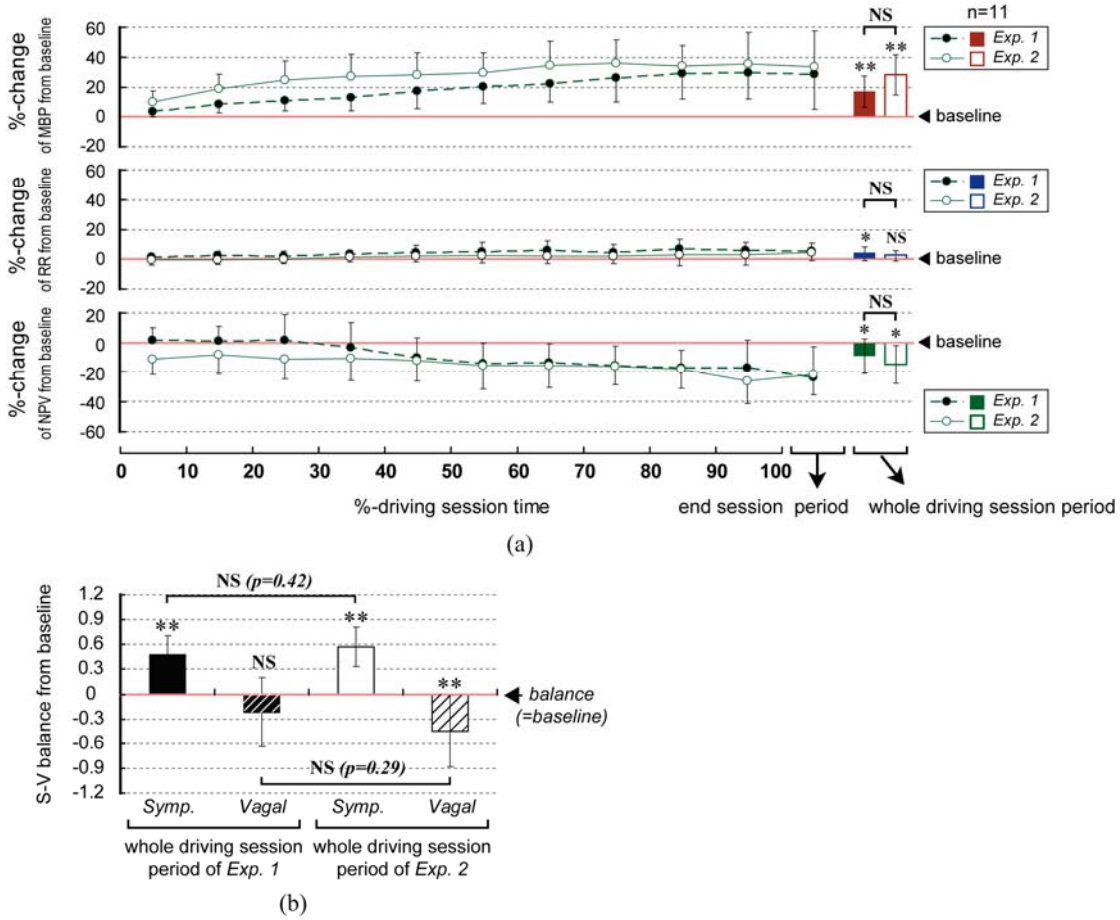

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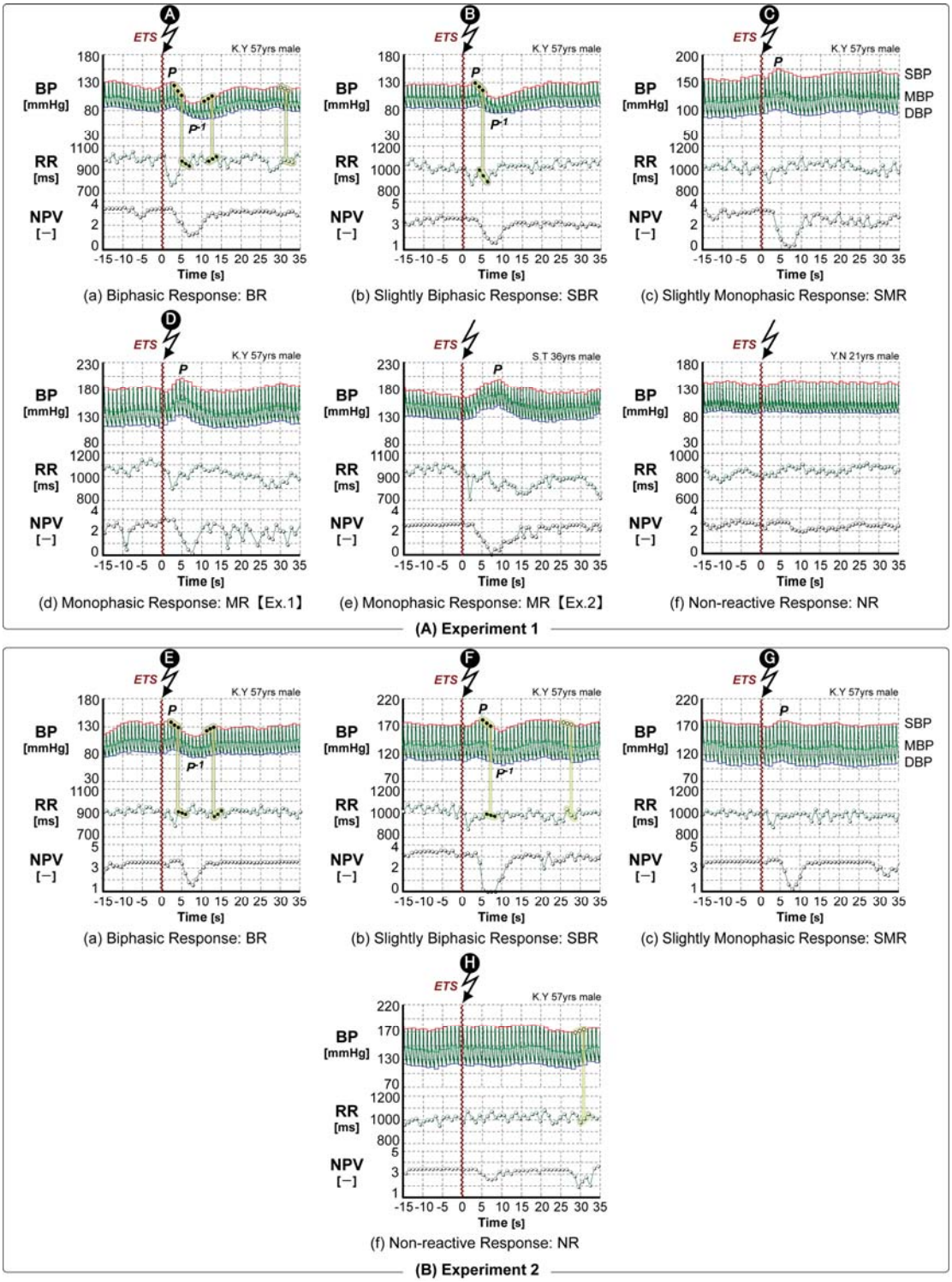

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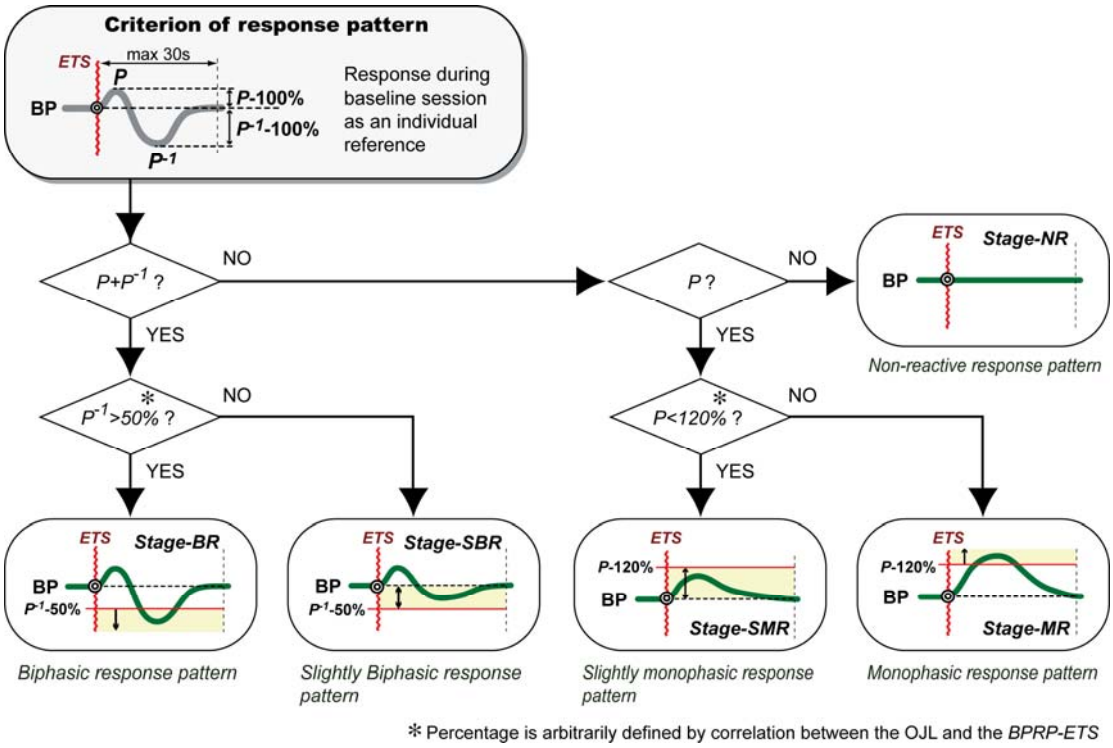

Figure 6 Schematic criteria for classification of BP response patterns following ETS (*BPRP-ETS*). See text for explanation.

Table 1 Experimental time of Experiment 1 and Experiment2.

	Experiment 1	***Experiment 2***
Sub no.	*min of experiment time*	*min of driving time*
A	85.0	65.5
B	120.0	89.3
C	120.0	120.0
D	53.0	82.5
E	90.0	79.0
F	60.0	19.5
G	100.0	69.5
H	90.0	80.0
I	110.0	120.0
J	120.0	120.0
K	30.0	30.7
mean	88.9	79.6

Table 2　Frequency distribution between activation state criteria (*Level-0 ~ -3*) and *BPRP-ETS* (*Stage-BR, -SBR, -SMR, -MR, and -NR*).

(a) Exp. 1

Criterion	*BPRP-ETS*					
	Stage-BR	*Stage-SBR*	*Stage-SMR*	*Stage-MR*	*Total*	*Stage-NR*
Level-0	18	1	0	0	19	0
Level-1	11	14	1	0	26	6
Level-2	4	7	15	7	33	9
Level-3	0	0	2	15	17	2
Total	33	22	18	22	95	17

Kendall's rank correlation coefficient: 0.763 (p<0.0001)

(b) Exp. 2

Criterion	*BPRP-ETS*					
	Stage-BR	*Stage-SBR*	*Stage-SMR*	*Stage-MR*	*Total*	*Stage-NR*
Level-0	33	2	0	0	35	1
Level-1	14	18	2	0	34	12
Level-2	3	5	26	2	36	15
Level-3	0	0	0	1	1	0
Total	50	25	28	3	106	28

Kendall's rank correlation coefficient: 0.747 (p<0.0001)