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Detection and Prediction of Drowsiness by Reflexive Eye Movements

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Abstract—**A reliable predictor of drowsiness using objective measures is desirable for machine and vehicle operations in which human errors may cause fatal accidents. We have evaluated the Vestibulo-Ocular Reflex (VOR) as a possible predictor of drowsiness. The VOR is a compensatory eye movement that stabilizes retinal image during head motion, and is inevitably induced by vibration in a car running on the road. We employed an uneventful driving simulation (DS) featuring vibration stimulation to induce both drowsiness and VOR in healthy human subjects. VOR performance was characterized by its gain and variability, and evaluated in relation to the subjects' drowsiness. A significant decrease in VOR gain and increase in variability accompanied subjective sleepiness, with the changes occurring before subjects became aware of sleepiness. From this finding, we developed a reliable method (88.9% accuracy) to predict oncoming sleepiness using changes in VOR performance as a cue.**

I. INTRODUCTION

An objective measure of drowsiness is highly useful for preventing accidents caused by human error in factory and vehicle operations. An optimal metric should detect drowsiness at the earliest possible stage, allowing preventive treatments before the machine operator or the vehicle driver loses control of an object. In a previous report, we demonstrated that the pupil of the eye is a reliable predictor of drowsiness as it starts to constrict before the subjects experience a subjective sensation of sleepiness [1]. It is a useful predictor of sleepiness in a relatively constant-illuminance environment such as cloudy/rainy daytime and at night where the pupillary light reflex is not strongly induced. In the current study, we evaluate another possible predictor of drowsiness that can be used under any visual conditions, the vestibuloocular reflex (VOR) [2-4]. A popular model system in studies of biological motor control and learning, the VOR is a reflexive eye movement that counter-rotates the eyes during head motion to stabilize gaze direction in space and prevent image slippage on the retina. Although the shortest neuronal pathway subserving this reflex comprises only three synapses (the "three-neuron arc"), it has been shown that the performance of the VOR is severely degraded when the subject is sleepy [5]. When driving, a driver's head moves continuously due to roughness of the road. Thus, the VOR is a possible detector of drowsiness for car drivers. However, its potential as a predictor of drowsiness has not yet been evaluated. In this study, we employed a monotonous driving simulation to evaluate the VOR as a detector and predictor of drowsiness.

II. METHODS

A. *Experimental setup*

A schematic diagram of the experimental setup is shown in Fig.1. Each subject sat comfortably on the driver's seat equipped with a steering wheel, brake, and accelerator pedals (Logicool · PRC-11000) in a dark room. The subject wore goggles (NEWOPTO · ET-60-L) with 2 CCD cameras, each of which takes infrared images of each eye at 29.97 frames per second (NTSC). Three -axis accelerometers and three-axis angular velocity meters were attached to the goggles to record the subject's head motion. Electro-cardio gram (ECG) and respiratory wave (RW) data were also recorded. These signals were synchronized with the video images by Spike2 software (Cambridge Electronic Design), and digitized/stored in a hard drive at the sampling rate of 1000Hz through Power1401 AD/DA device (Cambridge Electronic Design). The same data were branched and fed into another PC by LabVIEW software (NATIONAL INSTRUMENTS) for the purpose of real time monitoring of pupil diameter, eye movement, heart rate, and respiration.

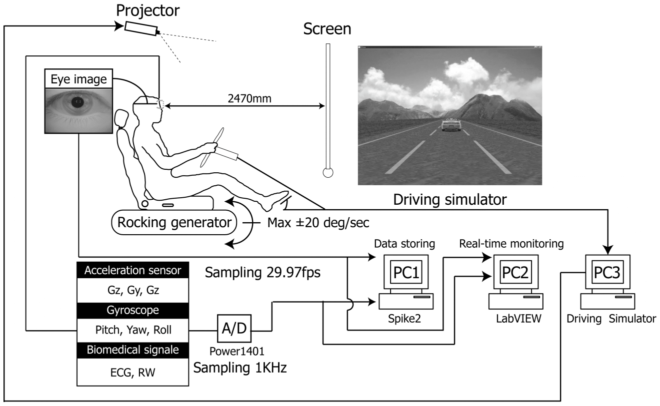

Fig. 1. Schematic diagram of the driving simulation setup.

B. *Driving simulation (DS)*

The driver's seat in which subjects were comfortably seated simulated the swaying motion of driving on the road,

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thereby inducing the pitch and vertical head movements typical during driving [6]. The subjects practiced the DS operation for one minute and adapted to the room luminance level for 10 minutes prior to the DS experiment. They were instructed to follow the car in front, and drive on the straight road at the maximum speed. Only the white lane markings and texture of grass on the shoulder of the road moved radially backward depending on the speed of the car during the DS. The subjects were asked to report the degree of their sleepiness every two minutes during the DS. The degrees of sleepiness employed were as follows: level-0: not sleepy, level-1: not sure if sleepy or not, level-2: sleepy, level-3: more sleepy than level-2, level-4: more sleepy than level-3, and so on. The DS visual scene was generated by a custom program running on a PC, and projected onto the screen 264cm away from the subject's eyes. The horizontal and vertical visual angles of the image were ±12.1, and ±10.7 deg, respectively. The DS duration was 10 to 15 minutes. A total of 11 healthy subjects aged 23.3 ± 6.8 years (mean ± SD) participated in the experiment. The subject recruitment and experimental procedures for this study conformed to the Declaration of Helsinki. Most of the subjects were university students, and all gave informed consent.

C. Data analysis

The recorded data were analyzed off-line in MATLAB (Mathworks). Using custom-made scripts, from each frame of the videotaped eye images, eye position was measured as the center of the pupil. Eye position was measured from the center of the pupil for each frame of the videotaped eye images using custom scripts. Errors in the measurement of eye position due to blinks and saccades were eliminated automatically [5]. The eliminated periods of data were interpolated using a linear function. The measured eye positions [mm] were converted to angular eye position θ [deg] by the following equation:

$$\theta = 2\sin^{-1}\left(\frac{l}{2r}\right) \qquad (1)$$

where l denotes the difference in eye positions [mm] between previous and current frames, and r denotes the radius of the average adult eye ball (12mm). Angular eye velocities $e(t)$ [deg/s] were calculated by a low-pass differentiation filter. Ideal angular eye velocities e_{ideal} to perfectly compensate for head motion were calculated as follows:

$$e_{ideal}(t) = e_{ideal\,y}(t) + e_{ideal\,p}(t) \qquad (2)$$

where $e_{ideal\,p}$ is the sign-reversed head pitch rotational velocity measured by the gyroscope attached to the goggles, and

$$e_{ideal\,y}(t) = \frac{d}{dt}2\sin^{-1}\left(\frac{y(t)}{2L}\right) \qquad (3)$$

where $y(t)$ is vertical head displacement estimated as the 2nd integration of the vertical head acceleration, and L denotes the distance between the eye and the fixation point on the DS screen. In all the subjects who participated in this study, head pitch rotations ($e_{ideal\,p}$) were the majority (99%) contribution to the ideal head velocity value, thus were employed as e_{ideal}. Using ideal eye velocity e_{ideal} and the actual measured eye velocity $e(t)$, VOR gain G_{VOR} was estimated to minimize the square sum of the residual $\varepsilon(t)$ in the following linear regression equation:

$$e(t) = G_{VOR}e_{ideal}(t-\tau) + dc + \varepsilon(t) \qquad (4)$$

where τ is the latency of eye movements in response to head motion. We evaluated VOR gain and the standard deviation of $\varepsilon(t)$ as measures of VOR performance.

III. RESULTS

Fig. 2 shows eye velocity and ideal eye velocity traces, and their relationship when the subject was awake (a and b) and sleepy (c and d). When the subject was awake, the eye velocity trace is similar to the ideal eye velocity trace, resulting in a linear relationship whose slope (G_{VOR}) is close to 1 (0.802) and the standard deviation of the residual (*SDres*) is small (1.017). In contrast, when the same subject was sleepy, his eye velocity trace deviated from the ideal eye velocity trace, resulting in large variability in their relationship (d) with a smaller regression slope (0.673) and larger *SDres* (2.964). This was observed consistently in all the subjects who became sleepy in the DS experiment. Thus both VOR gain and *SDres* clearly indicate the subject's sleepiness.

We further evaluated the possibilities of these parameters as predictors of subjects' sleepiness. Fig. 3 illustrates changes in VOR gain and *SDres* together with the subject's sleepiness level during the DS. This subject started to report sleepiness (sleepiness level 2 or higher) 8 minutes after the beginning of the DS. Interestingly, changes in *SDres* and VOR gain were evident in advance of the subject's reports of feeling sleepy. At least one of the two parameters started to change in advance of the subjective sensation of sleepiness in all the subjects tested in the experiment, indicating that considered together, they can predict sleepiness.

The values of VOR gain and *SDres* vary by subject. VOR gains of some subjects are close to unity whereas some have lower VOR gains even when they are awake. The same is true for *SDres*. To account for inter-subject variability and detect/predict sleepiness by use of a simple algorithm we

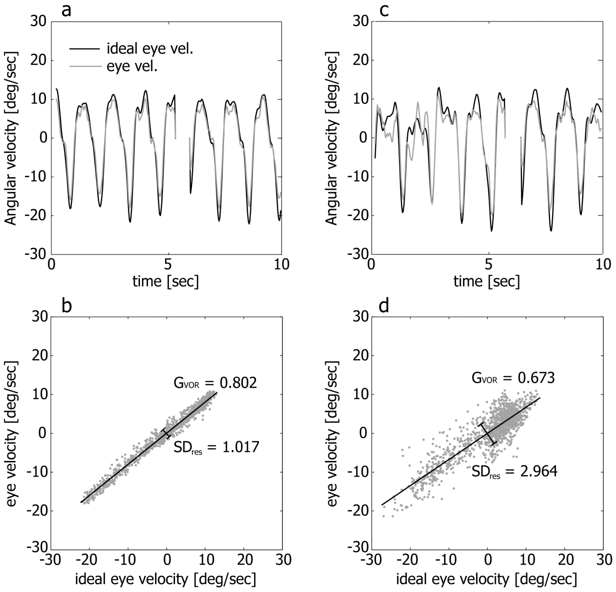

Fig. 2. Examples of VOR when the subject was awake (a) and sleepy (c) during the DS. Gray traces are the ideal eye velocities to compensate for head motion during the DS. Lower panels are relationship between the ideal eye velocity and induced eye velocity as VOR when the subject was awake (b) and sleepy (d).

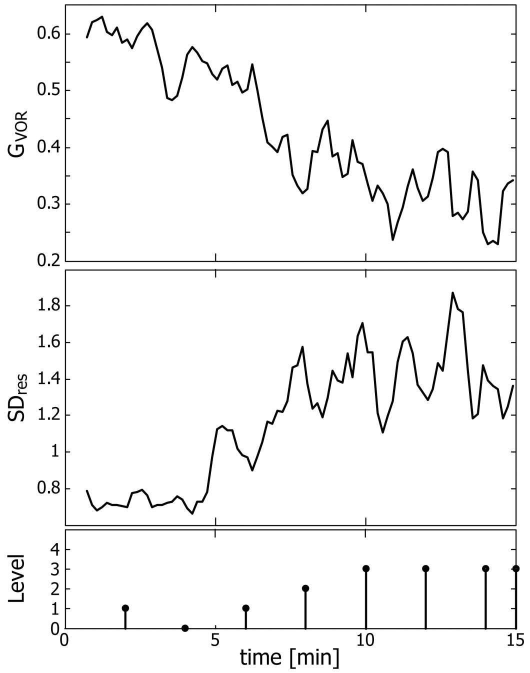

Fig. 3. Example of changes in VOR gain (top), *SDres* (middle), and the sleepiness level (bottom) during the DS.

employed the following indices:

$$\Delta G_{VOR}(t) = -\frac{G_{VOR}(t) - \overline{G_{VOR}}}{\overline{G_{VOR}}} * 100 \tag{5}$$

$$\Delta SD_{res}(t) = \frac{SD_{res}(t) - \overline{SD_{res}}}{\overline{SD_{res}}} * 100 \tag{6}$$

where $G_{VOR}(t)$ and $SD_{res}(t)$ are instantaneous VOR gain and *SDres* calculated using the data from a time window *t* - 40 to *t* seconds. $\overline{G_{VOR}}(t)$ and $\overline{SD_{res}}(t)$ are mean VOR gain and *SDres*, respectively, from the first 100 seconds of the DS during which each subject was fully alert. Thus, $\Delta G_{VOR}(t)$ and $\Delta SD_{res}(t)$ are VOR gain and *SDres* calculated for the last 40 sec and normalized using the baseline "awake" VOR performance values. The 40 second time window was determined to be the shortest possible sample that generated reliable estimates. Fig. 4a illustrates scatter plots of $\Delta G_{VOR}(t)$ vs $\Delta SD_{res}(t)$ from 7 subjects who reported a sleepiness level 2 or higher (sleepy) during the DS. Black dots are data from the initial 100 seconds in which the subjects were highly aroused, whereas crosses are data from when their sleepiness level was greater than or equal to 2 (sleepy). The area containing 100% of the data points from the awake period (gray) was delimited using threshold lines (dotted, th1 and th2). This area ("arousal area," hereafter) contained only 5% of the data from sleepy periods, indicating that data from awake and sleepy periods could be reliably separated. Fig. 4b plots $\Delta G_{VOR}(t)$ vs $\Delta SD_{res}(t)$ of the same 7 subjects when their sleepiness levels were smaller than 2 (not sleepy). Interestingly, many data points are plotted outside of the arousal area even though they were not yet sleepy, suggesting that either one or both parameters started to move outside of the arousal area into the "sleepy area" before the subjects reported perceiving sleepiness. Fig. 4c illustrates changes in $\Delta G_{VOR}(t)$ and $\Delta SD_{res}(t)$ in a subject whose sleepiness level reached 2 or above at 8 minutes during the DS. Dotted lines labeled as th1 and th2 are the same threshold values in Fig. 4a and b. In this example, $\Delta G_{VOR}(t)$ exceeded the threshold th1 at around 2 minutes but soon came back below the threshold, then exceeded it again at around 3 minutes, while $\Delta SD_{res}(t)$ stayed below its threshold th2 until around 5 minutes. In other subjects (data not shown), $\Delta SD_{res}(t)$ exceeded the threshold before $\Delta G_{VOR}(t)$ crossed th1. From these observations, we can predict subjects' sleepiness when either $\Delta G_{VOR}(t)$ or $\Delta SD_{res}(t)$ exceeds each threshold continuously for 40 seconds. The 40-second margin was given to prevent false positives. In the case of the subject in Fig. 4c, the prediction can be made 260 seconds before the subject started to perceive sleepiness at 8 minutes. Over 9 samples from the 7 subjects, the proposed method was successful to predict oncoming sleepiness in 86% of the cases, and the average prediction time was 112.5 seconds prior to subjects' perception of sleepiness.

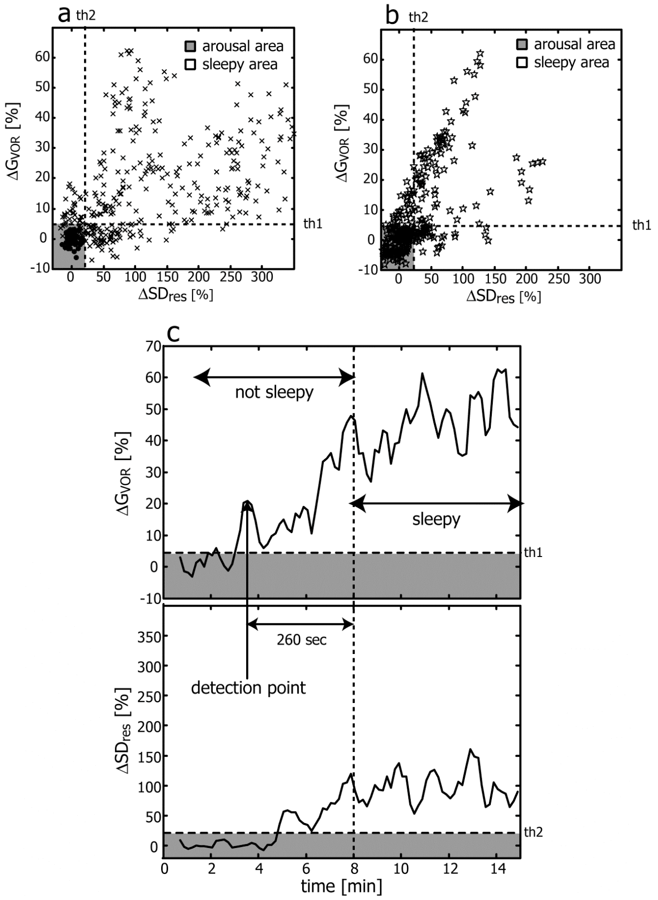

Fig. 4. Normalized VOR gain ($\Delta G_{VOR}(t)$) vs normalized standard deviation of the residual ($\Delta SD_{res}(t)$) from 7 subjects who reported sleepiness at level 2 or higher (sleepy). A: when the subjects were highly aroused (initial 100 seconds of the DS; black dots), or sleepy (sleepiness level 2 or higher; crosses). B: when the subjects were not yet sleepy (sleepiness level less than 2). C: changes in $\Delta G_{VOR}(t)$ and $\Delta SD_{res}(t)$ of a subject whose sleepiness level reached 2 or above at 8 minutes during the DS.

IV. CONCLUSION

In this study, we demonstrated that the performance of the VOR as characterized by VOR gain and the standard deviation of the residual component (*SDres*) can be a reliable predictor of sleepiness. The VOR is inevitably induced while driving a car due to the roughness of the road. Thus VOR performance is a practically useful predictor of sleepiness for car drivers. It was shown that in more than 86% of the subjects, their oncoming sleepiness could be predicted a few minutes in advance. This information is significantly useful for preventing drivers from falling asleep at the wheel. The algorithms employed here to calculate VOR gain and *SDres* are simple, thus allowing real time execution of these parameters, given detection of a driver's head and eye movements. Recently, such technologies applicable in a car have been developed based on real-time image processing to estimate face direction in 3D [7], and the 2D position of the pupils [8].

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