Fatigue evaluation by detecting blink behaviour using eyeglass-shaped optical sensor system

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Published in Micro & Nano Letters; Received on 28th February 2017; Revised on 23rd May 2017; Accepted on 7th June 2017

Death from overwork and severe accidents caused by mental fatigue and sleepiness are becoming one of the more pressing social problems of developed countries. Such mental fatigue and sleepiness often comes from declines and/or changes in wakefulness in our daily life. Recently, numerous researchers have focused on possible ways of utilising physiological signals to deduce alertness; however, the characteristic behaviours that can be used to deduce wakefulness are difficult to measure. To better understand the indices of change in wakefulness states, the authors fabricated a micro-optical sensor system that can measure physiological signals from eye and eyelid conditions without imposing stress on the user. Using the newly fabricated micro-optical sensor system, they have found and reproduced characteristic blink behaviours that are indicative of changes in a person's wakefulness. Herein, new indices are proposed that have potential for use in fatigue evaluation tests. The experimental results demonstrate that the sensor system can detect declines in and/or changes in wakefulness that indicate mental fatigue and sleepiness.

1. Introduction: Overwork and stress in workplaces can trigger a number of critical illnesses including cardiac disease and depression [1, 2]. In many countries, death from overwork is now becoming one of the most serious social problems. In Japan, the number of suicides due to overwork was 855 in 1978. However, it gradually increased to over 2000 in 2015 [3].

Furthermore, the number of patients suffering from mental illness is drastically increasing as well [3], and even before mental illness and chronic fatigue can reach the level of the serious cases mentioned above, low-work efficiency can trigger severe and sometimes fatal accidents. With the ever-increasing demand for ways to measure of both mental and physical fatigue, a wide variety of research efforts into fatigue-related ailments have been conducted.

In Japan, professional research targeting working people first began in 1910. In 1925, several physiological signals, such as body temperature and heart pulse, were found to have strong correlations with fatigue and stress. For example, it is now known that heart rate variability decreases as workloads increase [4]. Electroencephalograms provide another method that can measure psychological conditions, among which the α-wave typifies the resting state, the β-wave shows the exited state, and the θ-wave reflects imagination [5].

However, since the monitoring of such physiological signals – and thus fatigue and stress – must be conducted in real-time and without interfering with the worker's efficiency, a number of monitoring systems based on wearable device systems have been proposed. Among the most familiar wearable device systems for monitoring physiological signals are wristband-mounted sensor systems that can be worn like watches [6]. Current examples include the Apple Watch, Microsoft Band, and Fitbit Surge, all of which are now commercially available. Most such devices utilise the wearer's heart rate to monitor his or her health state and have proved to be very reliable health monitoring devices.

In addition to the above, wearable eye tracking devices offer another known tool for physiological signal monitoring [7]. Such wearable eye tracking devices monitor eye and eyelid movements in order to detect health states.

When exhaustion strikes in the midst of work, those affected experience bleary eyes, an increase in the blink frequency, and slow blinks. Hence, we can say that the changes in wakefulness that lead to mental fatigue and sleepiness appear as evidence in the movement and characteristics of a person's eyelids and eyes. Previous research highlighted the relationship between blink behaviour and wakefulness state changes [8].

Now, eyelids and eyes can be monitored by eyeglasses-based wearable devices, which is advantageous since eyeglasses are one of the most familiar wearable devices. In our previous study, we fabricated an eyeglass-shaped optical sensor system that can extract information relating to eye movement and eyeball rotation. Fig. 1 shows a front view of our device.

The optical sensors are made of dye-sensitised photoelectric cells (DSSC) that are micro-patterned on the surface of an eyeglass lens. These fabricated sensors detect differences in light intensity reflected from the eye (pupil, white of eye, and eyelid). These light intensity differences are then converted into a voltage value that is processed to deduce eye movement and blinking. The proposed sensor system is easy to wear because of its eyeglass-shaped, lightweight, and because DSSC cells operate on ambient light, so no power source is required.

Since it does not use an external camera that faces the subject, users experience little stress. In our previous work, we attempted to correlate the recorded movements with mental fatigue utilising the US National Aeronautics and Space Administration Task

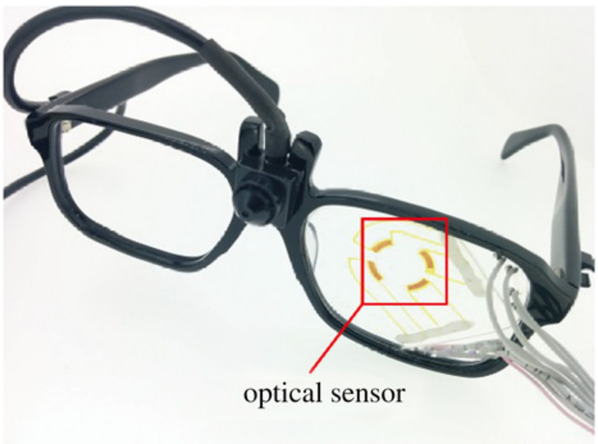

Fig. 1 *Eyeglass-shaped optical sensor system*

Micro & Nano Letters, 2017, Vol. 12, Iss. 8, pp. 554–559
doi: 10.1049/mnl.2017.0136

Load Index (NASA-TLX), which was developed to quantitatively estimate a subject's mental fatigue [8]. The results of multiple regression analysis implied that some of the blink behaviours are correlated to mental fatigue.

In this paper, we report on our continued search for indices that indicate change in wakefulness using our new optical sensor system. In particular, we conducted several experiments focusing on the characteristic behaviour of blinking. Fig. 2 shows a classification of blink types. Generally speaking, blinks can be divided into three types: reflective, voluntary, and spontaneous. Reflective blinks are accompanied by abrupt input stimuli [9]. Voluntary blinks are intentionally performed by subjects, such as by winking [10]. Spontaneous blinks are those that occur despite the absence of external factors. Therefore, since the characteristic behaviours related to spontaneous blinking are believed be relevant to change in wakefulness [11], detecting characteristic indices in spontaneous blinking can provide a very useful way to monitor changes in a subjects wakefulness in real-time.

In the field of physiological psychology, several indices that are considered to be associated with changes in wakefulness states have been reported. For example, a lengthening of blink duration (BD) and an increase in the number of blink (NB) bursts (intervals <1 s) have been correlated to a decline in wakefulness. BD is defined as eye closing time during blinking. A blink burst (BB) is defined as two or more blinks within 0.5–2.0 s [11]. Some previous study have stated that an increase in BBs with intervals of <1 s is related to a change in wakefulness, and the NBs was also been reported as a mental fatigue factor [12].

A drowsiness state determination can be made by detecting eye closing continuance [13]. In this paper, we provide proof that our new optical sensor system can detect reproduced characteristic indices of change in a subject's wakefulness state. In addition, we report on fatigue evaluation tests conducted to confirm whether our system can detect the characteristic indices present in spontaneous blinking.

Another purpose of our work is to discover new characteristic indices in spontaneous blinking that are closely related to subject wakefulness changes in the hope that they will lead to a method whereby mental fatigue assessments can be conducted in real-time using only the wearable eyeglass-type system.

2. Fabrication and principle: The proposed sensor system consists of DSSCs and an electrolyte. An overview of the fabrication processes used to produce our system is provided in Fig. 3. As can be seen in the figure, indium tin oxide (ITO) thin film mounted on a glass substrate is fine-patterned to form electronic circuits. We then apply and sinter titanium dioxide (TiO_2) nanoparticles and platinum pastes onto the ITO films in order to form the cathode and anode, respectively. The substrate with TiO_2 is immersed into a ruthenium complex colouring solution to attach the dyes. Holes are made in the glass substrate with platinum needles in order to inject the electrolyte. The two processed substrates are then bonded with heat and pressure via an adhesive tape to form channels for the electrolyte. Encapsulating the iodine compound electrolyte completes the processes. The durability of our micro-optical device depends on the encapsulation of electrolyte; however, it can generally be used for approximately one month.

As the optical sensors, the DSSCs detect the light intensity entering the TiO_2-side substrate. The detection principle of voluntary blinking is described in Fig. 4. Since the intensity of light reflected from the subject's eyelid is generally stronger than that from the eye itself, the output voltage of the two upper DSSCs rises rapidly when the subject blinks. The blinking voltage V_b is defined by the following equation:

$$V_b = V_U = \frac{V_{ul} + V_{ur}}{2} \quad (1)$$

The middle graph in Fig. 4 shows the output voltage when the subject blinks. Note that, due to the DSSC response speed, it takes ~100–200 ms for the output voltage to drop due to the blinks. As you can see in the middle graph in Fig. 4, the base value of the output voltage shows a slight increase because of the slow DSSC reaction rate. To detect the exact timing of the blink, the derivative of the voltage with respect to time or voltage change rate, is used. The formula is expressed by the following equation:

$$\mathrm{grad}V_b = \frac{V_b(0.2) - V_b(0)}{0.2} \quad (2)$$

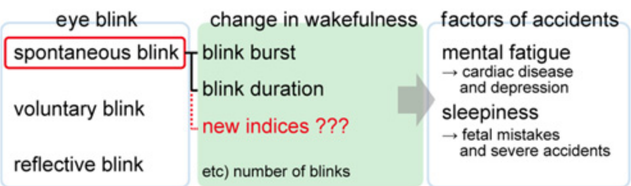

Fig. 2 *Classification of blink*

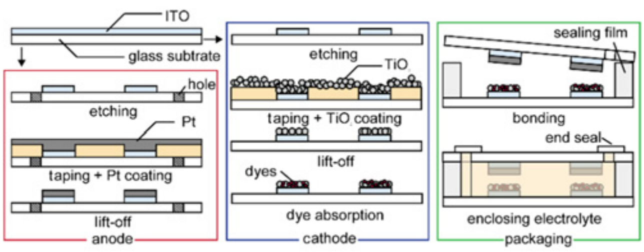

Fig. 3 *Fabrication processes*

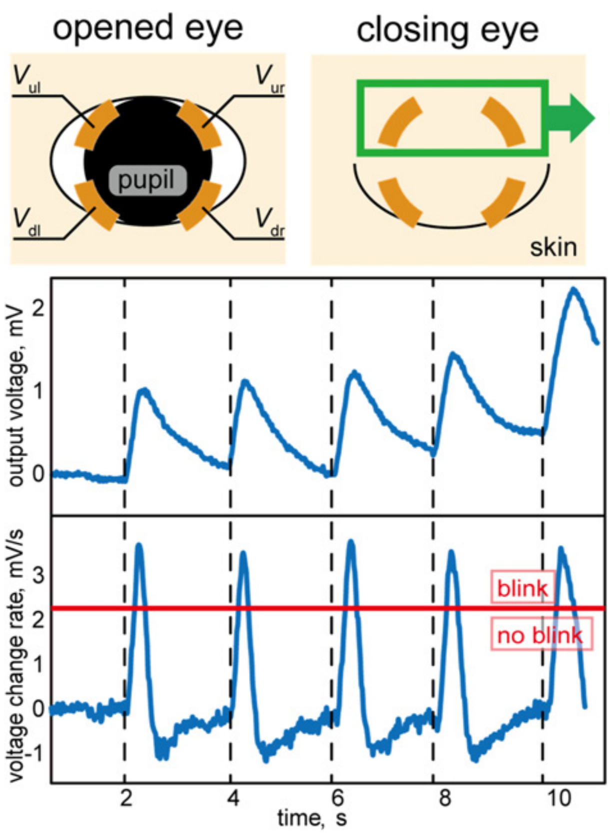

Fig. 4 *Voluntary blink detection principle*

doi: 10.1049/mnl.2017.0136

The lower graph in Fig. 4 shows the voltage change rate when the subject blinks. As can be seen in the graph, we set the threshold as the 70% of voltage change rate required to detect a voluntary blink [14]. Note that this absolute value varies with each subject, so calibration must be conducted before every experiment. However, the detection threshold for spontaneous blinking has yet to be determined because of the non-uniformity of its output voltage value. Furthermore, the intensity of incident light may fluctuate in practical applications. In such cases, we can employ another reference cell to detect the light reflected from the subject's skin and use the relative value to detect blinks by compensating for the fluctuation.

3. Experiments

3.1. Indices of wakefulness change

3.1.1. Eye state: As we mentioned earlier, the ultimate goal of our work is to identify a fatigue index that can be detected by our optical sensor system. To achieve this goal, it was first necessary conduct an experiment to classify the opened, blinking, and closed eye states, because those classifications enable us to detect the drowsiness conditions of the subjects.

We began with an experiment conducted under a constant light source with the test subject's head positioned at a 1 m distance from a focal point. Note that this condition remained the same throughout all the experiments discussed in this section. All subjects were briefed on the mechanism of our optical sensor system and each test subject was requested to perform the following actions for four 15 s cycles (60 s in total):

(i) open eyes (5 s),
(ii) blink every 1 s (5 s),
(iii) close eyes (5 s).

Using this process, we measured the output voltage for three test subjects.

3.1.2. Spontaneous blinking: Since spontaneous blinking is thought to accurately reflect a subject's mental condition, ensuring accurate detection of his or her spontaneous blinks is necessary [11]. In our previous study, the threshold for voluntary blinking was determined to be 70% of the voltage change rate. However, since there is a different duration for each spontaneous blink, we conducted an experiment aimed at determining the detection threshold for such blinks. In this experiment, test subjects were directed to gaze at a focal point 1 m away from their eyes and asked to blink spontaneously as necessary. The experiment duration was 3 min, and video footage of each test subject's spontaneous blinking was recorded for that period.

We then watched the video and counted the actual number of spontaneous blinks for each test subject, and used that figure to derive a spontaneous blink detection rate, which is defined as the following equation:

$$\text{detection rate (\%)} = \frac{\text{detected blinks by sensors}}{\text{observed blinks in video}} \times 100 \qquad (3)$$

3.1.3. Blink duration: In addition to spontaneous blinks, it has been reported that BD or eye closure time, provides another indicator of a person's wakefulness. More specifically, a lengthening of BD is a symptom of a person's increased drowsiness [15]. Accordingly, in our next experiment, we aimed at differentiating between two different BDs by requesting a test subject to perform the two types of blinks mentioned below. We then extracted the feature values of the different blink types in order to detect the BD:

(i) normal blink (every 2 s, 10 s in total),
(ii) slow blink (every 2 s, 10 s in total).

In this experiment, the 70% threshold was used to detect the BD because all these blinks were voluntary.

3.1.4. Blink burst: A blink burst is defined as more than two blinks that occur in as short a period as from 0.5 to 2.0 s. Such blink bursts have been reported to be strongly associated with changes in a person's wakefulness state [11]. Accordingly, we attempted to verify that our optical sensor system could detect such blink bursts accurately. To accomplish this, test subjects were requested to blink twice deliberately at regular intervals. From those blinks, we derived the voltage change rate.

3.2. Fatigue evaluation test: Based on the result of Section 3.1, we conducted fatigue evaluation experiments on 14 test subjects. These subjects were directed to perform the Uchida–Kraepelin (U–K) psychodiagnostic test, which was originally developed by Uchida [16]. This test, which is used as a representative performance test in many companies and government offices worldwide, measures a subject's ability to perform tasks quickly and accurately. It is also known as one of the simpler mental stressors that can be given to subjects. In other words, it is a reliable way to make people exhausted.

The U-K test is based on a series of simple addition tasks. Normally, the result of a U-K test is examined carefully to obtain an estimate of individual's performance characteristics. However, since we adopted the U-K test solely as a simple mental stressor, the actual test results were irrelevant, and thus not examined. U-K tests are divided into six sets, each of which is 10 min long. Subjects were given 1 min rest periods between each U-K test set.

The Visual Analogue Scale (VAS) was adopted as a clinical measurement of mental fatigue in our study. While this scale was originally developed to quantify pain sensations in tested subjects, numerous articles have shown that the VAS can also be used to measure subjective feelings, such as fatigue [17]. The VAS uses a 100-mm-long straight line drawn on a white paper, one end of which is marked 'vigorous', the other 'exhausted'. Test subjects were instructed to make marks on the line based on the subjective level of fatigue they experience.

In our experiment, subjects indicated their subjective fatigue states during the rest periods. After each subject had completed the entire test, we then measured the length between the line end and the mark to gain indications of the subject's subjective impression of their mental fatigue. The experimental conditions were the same as those set forth in Section 3.1. After each subject was tested, we attempted to correlate their fatigue levels with several other parameters related to blinks that were acquired by our system.

4. Result and discussion

4.1. Indices of wakefulness change

4.1.1. Eye state: Fig. 5*a* shows the output voltage when three subjects were directed to perform the requested eye states, and from which the characteristic behaviour of each eye state was obtained in the form of voltage. The attributes considered were eye colour, distance between the eyes and the optical sensors, and BD time. To classify the eye state output voltage into the three parts (open, blinking or closed), several thresholds were used. For blink detection, we used the same 70% voltage change rate selected in our prior work, while for closed-eye detection, we used the maximum blink voltage.

As can be seen in Fig. 5*a*, the closed eye voltage value is higher than the blink value, which means the closed-eye condition can be distinguished from the blink state. Based on these considerations, the output voltages of all subjects were converted into Class 0, 1, and 2, as summarised in Fig. 5*b*.

4.1.2. Spontaneous blinking: Fig. 6 shows the detection rate for spontaneous blinks using voltage change rate thresholds ranging from 50 to 100%. As can be seen in this figure, higher detection

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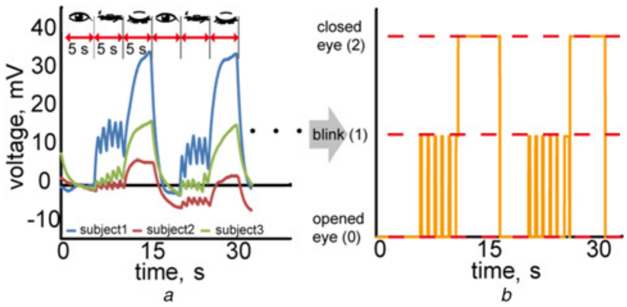

Fig. 5 *Output voltage (Fig. 5a), classification of eye state (Fig. 5b)*

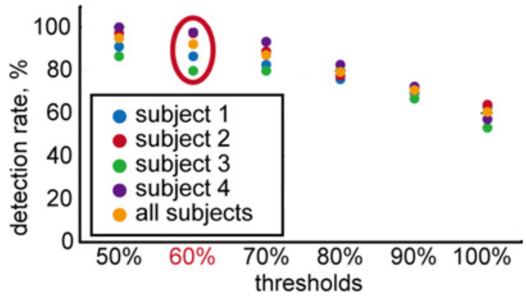

Fig. 6 *Voluntary blink detection rate*

rates were achieved with the lower thresholds. The threshold of 50% showed the highest spontaneous blink detection rate, whereas thresholds smaller than that level resulted in false-positive detection errors due to signal noise. On the other hand, the 60% threshold could detect 92.3% of all spontaneous blinks without false-positive detection errors. Therefore, we consider the 60% threshold to be adequate for acquiring a subject's spontaneous blinks, while 70% is suitable for voluntary blinks.

4.1.3. Blink duration: Fig. 7*a* shows a typical output for the different BDs. As you can see, BDs with various lengths were obtained. We then conducted a student *t*-test to confirm that our system can distinguish the different types of BDs based on statistical significance. As shown in Fig. 7*b*, significant differences were confirmed among each BD, thereby confirming that our optical sensor system is capable of distinguishing the different BD types.

4.1.4. Blink burst: Fig. 8 shows a schematic diagram of the voltage change rate when a subject displayed two blink bursts. We detected this blink burst using the threshold of 70%. Table 1(a) shows the detected intervals between the first and second peaks. The ability to detect such intervals indicates that our system can identify blink bursts. However, the table also shows we missed several

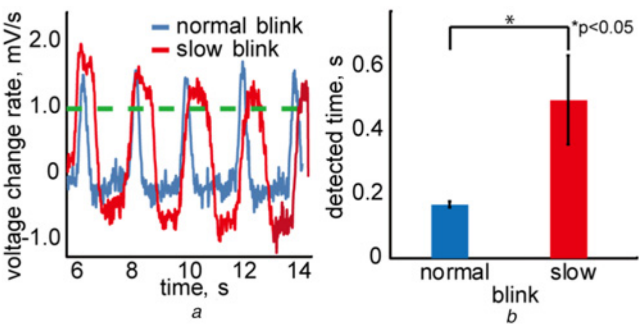

Fig. 7 *Voltage change rate (Fig. 7a), comparison of BB (Fig. 7b)*

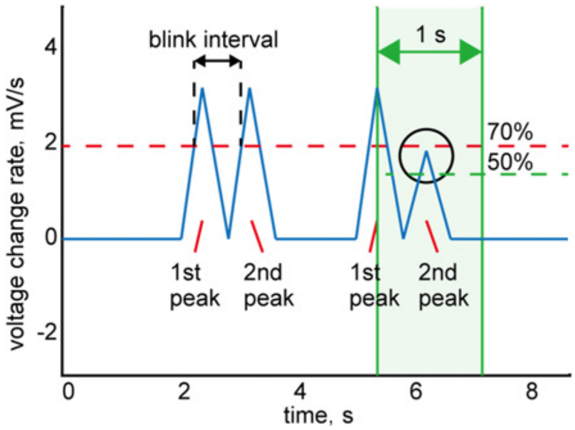

Fig. 8 *Schematic diagram of BB*

Table 1 (a) Detected BB, (b) Detected BB with a new threshold

	Subject 1	Subject 2	Subject 3	Subject 4
1	0.6	0.56	0.52	0.6
2	0.4	0.54	0.54	failure
3	0.54	failure	0.54	failure
4	0.42	0.52	0.4	failure
5	0.38	failure	0.48	failure
average	0.46	0.54	0.49	0.6

	Subject 1	Subject 2	Subject 3	Subject 4
1	0.6	0.56	0.52	0.6
2	0.4	0.54	0.54	0.56
3	0.52	0.580	0.54	0.68
4	0.42	0.52	0.4	0.52
5	0.38	failure	0.48	0.58
average	0.46	0.55	0.49	0.58

blink bursts because the second blink burst peak is often too small to be detected by the threshold described in Fig. 8.

It is inferred that a gradual decrease in voltage reaction quantity occurs each time the test subjects blink, which makes the second peak smaller. Therefore, another method of detecting the second peak of a blink burst is necessary. Some reports say that an increase of the blink burst interval <1 s is closely associated with a decrease in a subject's wakefulness state [11]. Thus, we defined a new threshold in order to detect the second peak after the first blink. Based on our spontaneous blink detection result, we set a 50% threshold for voltage change rate for the second blink after the first blink of a burst is detected. Table 1(b) shows the detected blink intervals with the new threshold. Here, it can be seen that all but one of the blink bursts were appropriately detected.

4.2. Fatigue evaluation test: After confirming our optical sensor system's ability to detect blinking via the voltage output of the sensor system, we next considered the fatigue evaluation test results using information for 11 of the 14 participating test subjects. Fig. 9 shows the VAS results obtained through fatigue evaluation testing. As can be seen in the figure, subjective mental fatigue levels gradually increased through the six U-K test sets for nine of the 11 test subjects.

These gradual increases of VAS average value indicate that the test subjects continuously accumulated mental fatigue over the test period. Note that two test subjects excluded from Fig. 9 actually

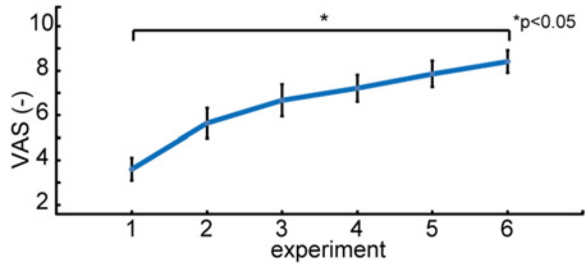

Fig. 9 *Result of VAS with subject average*

fell asleep momentarily during the test, after which their VAS result gradually increased. Next, in a *t*-test conducted to provide statistical strength to the VAS result, we found that there is a significant difference between the first and sixth sets of the VAS ($p < 0.001$). Therefore, we conclude that the U-K test effectively imposed mental fatigue on the test subjects.

Voltage change rates were calculated from the detected output voltage in order to obtain the information of subject's blinks during fatigue evaluation test. Based on the Section 4.1 results, several parameters that were associated with subject's mental fatigue were deduced. The parameters are NB, NB burst (BB), and BD.

In addition to these parameters, several candidate parameters were also examined as potential new mental fatigue indices. The candidate parameters we selected are the blink burst rate (BBR) and the velocity of blink (VB). The BBR is a ratio of the NB bursts to the number of the blinks, while the VB is defined as the average value of voltage change rate when the subjects blink. This parameter represents the eyelid movement speed. All parameters were calculated for each U-K test set. Fig. 10–14 show the time series variations of all examined parameters. In this experiment, all the parameters were normalised by the result of the first set. Statistical analysis was conducted by *t*-test.

NB time series variations, excluding those who fell asleep, are shown in Fig. 10. Here, a gradual increase of NB is confirmed and there is a significant difference between first and sixth set

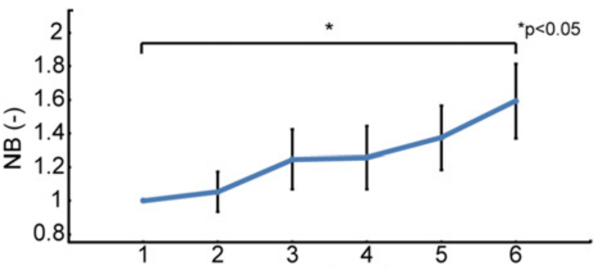

Fig. 10 *NB variation against repeated trials of UK-test*

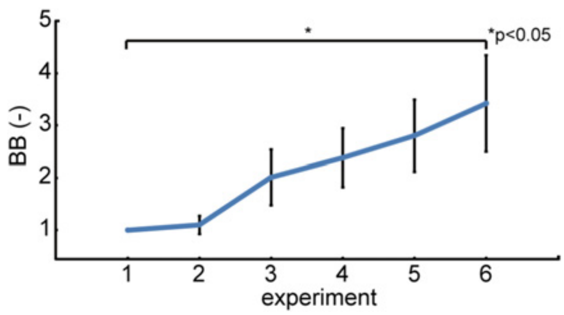

Fig. 11 *BB variation against repeated trials of UK-test*

($p = 0.008$). Thus, it is considered likely that this parameter is related to mental fatigue.

Observed BB time series variations (excluding those who fell asleep) are shown in Fig. 11. Here, a gradual increase of BB was observed and significant differences between the first and the sixth fatigue evaluation sets were confirmed ($p = 0.009$). Therefore, it can be said that BB correlates well with mental fatigue.

In the BD time series variations shown in Fig. 12, it can be seen that BD decreases until the fourth set and then increases. This indicates that the eye closure time recovers after 40 min of the fatigue evaluation test, and no significant differences between the first and 6th set were observed. This experimental result indicates it is uncertain whether BD is related to mental fatigue. Moreover, this result does not agree with our previous work [15].

The BBR time series variations are shown in Fig. 13. Here it can be seen that BBR increases rapidly until the third set, and then remains flat until the sixth set. Thus, a significant difference between the first and sixth set can be confirmed ($p = 0.032$), and it can be inferred that BBR is related to changes in subject wakefulness. However, there is no significant difference after the third set of fatigue evaluation, even though that this parameter rapidly increases during the first 30 min of testing.

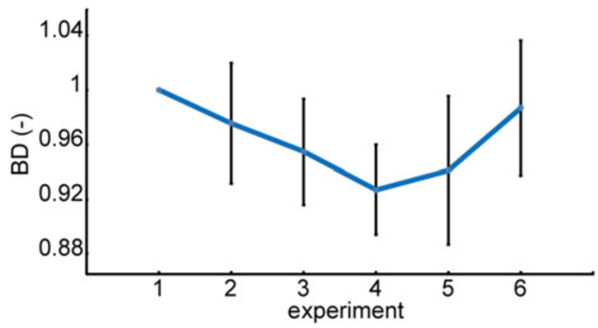

Fig. 12 *BD variation against repeated trials of UK-test*

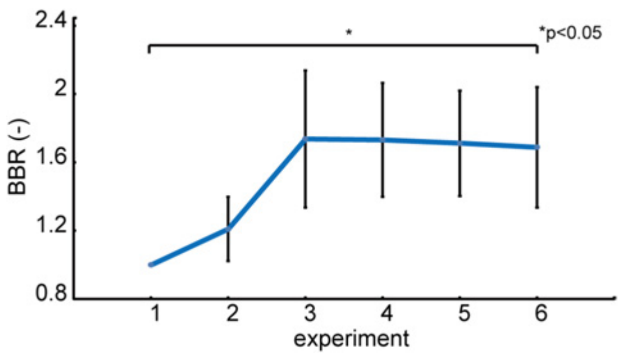

Fig. 13 *BBR variation against repeated trials of UK-test*

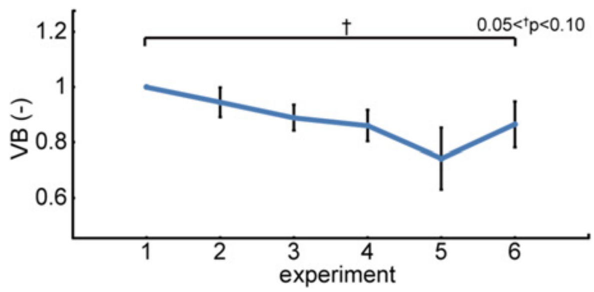

Fig. 14 *VB variation against repeated trials of UK-test*

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doi: 10.1049/mnl.2017.0136

The VB time series variation is shown in Fig. 14. Here, a slight decrease in this parameter can be seen, and there is a significant trend between the first and sixth sets of the test ($p = 0.066$). Therefore, we can say the VB could provide a mental fatigue indicator.

5. Conclusion: In this study, we conducted experiments to demonstrate that our optical sensor system can detect the changes in wakefulness that lead to mental stress and sleepiness. Throughout our experiments, we succeeded in detecting reproduced characteristic behaviours such as a blink duration lengthening and BBs. We also conducted fatigue evaluation tests based on those obtained indices and found that the NBs and the BB increased as the subject's mental fatigue accumulated, which was in keeping with the results of our previous work. However, lengthening of BD could not be validated via the fatigue evaluation tests, which was in contrast with our previous work. Based on the results of this study, we selected two candidate parameters, the BB rate and the VB, and carefully examined them. The BB rate was found to have a good correlation with fatigue, whereas the VB showed less potential utility.

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