Mental fatigue measurement as application software on consumer devices

— Introducing reliable fatigue index to daily life —

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Monitoring mental fatigue is critical for traffic safety and health care. Various indexes of mental fatigue have been developed and used in the fields of ergonomics and industrial hygiene. One such index is the flicker-perception frequency threshold: the frequency at which the perception of flickering lights disappears for human observers. This index has a long history as a reliable indicator of mental fatigue in the laboratory setting. We have developed low-cost technologies for measuring mental fatigue objectively with widely available consumer devices such as personal computers and smartphones.

Keywords **:** Mental fatigue, flicker perception threshold, personal mobile device, traffic safety

1 Objective of research and background of related technologies

The accumulation of mental fatigue in daily living is not only an issue of health management where overwork may negatively affect health, but also is a serious social and economic issue where such fatigue may link directly to decreased work efficiency or traffic accidents caused by reduced wakefulness. Particularly, drowsy driving and reduced attention due to overwork have been indicated as some of the major factors of serious traffic accidents in commercial vehicles such as freight trucks,[1] and the realization of technology that allows evaluation of daily fatigue condition without excessive economic cost has been highly in demand. Therefore, our objective was to quickly develop a technology that allows objective and quantitative monitoring of mental fatigue level at low cost, easily done on a daily basis, using the information device that are commonly available.

Meanwhile, there have been several indices developed for the quantitative evaluation of mental fatigue condition, and these were used mainly for research purposes. The major methods can be listed as follows:

A. Subjective index
− Self-conscious index:
  Subjective symptoms of fatigue (QA sheets and questionnaires)[2]

B. Objective index
− Behavioral index:
  For the required task, workload and frequency of error during work[3]
  Changes in movement and posture unrelated to required task[4]
− Physiological index:
  Respiration, pulse rate, sweating,[5] Electroencephalography (EEG),[6] etc.
− Perception and cognition index:
  Flicker perception threshold of visual stimulus[7]
  Spatial discrimination threshold of tactile stimulus[8]
− Biochemical index:
  Metabolites in saliva, urine, or blood; genetic expression; etc.[9]-[11]

In the measurement of fatigue based on above objective indices, the measurement and analysis of data or samples were conducted using special equipment under supervision of the test administrator, and the data were interpreted as part of the research activity. Therefore, it was impossible for ordinary users to use them readily in their daily lives. For example: (i) for the measurement of behavioral index, the performance evaluation specialized for particular tasks must be conducted, and it is necessary to record the subject's actions from a third-party viewpoint using cameras as well as conduct advanced image processing; (ii) to use the physiological signals such as respiration or pulse rate, a transducer is necessary to convert such signals into digital data that can be handled on portable information terminals; and (iii) to use the biochemical index, it is necessary to have specialized equipment for collecting and analyzing biological samples. Hence, the realization of a system that can be used by general users in the course of their daily lives was difficult. In contrast, for the sensory and cognitive indices,

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if there is a presentation of sensory stimuli to evoke visual, auditory, or somatic perception, as well as a way to collect responses from the user, it may be possible to achieve a system using a device to which we have daily access.

2 Scenario for realizing a fatigue measurement system that can be used in daily life

We decided to develop a technology that enables the quantitative evaluation of fatigue based on the changes in flicker perception that is presented visually using general-use electronic devices such as smart phones, personal computers, or car navigation systems.

There is a frequency threshold at which "flickering" can be perceived when the frequency of the intermittent point-light stimulus is gradually decreased (this is called the critical fusion frequency or critical flicker frequency, CFF) (Fig. 1). Since it was first reported in 1941 that CFF declined with accumulation of fatigue,[7] it became widely known as a quantitative measure for degree of fatigue. Since CFF has the properties that (i) change monotonically in time with continuous workload (that is, accumulation of fatigue), and (ii) are stable with small fluctuations between measurements, it has been used as an important research tool in the field of industrial health, industrial physiology, and traffic psychology (flicker test).[12][13] The flicker test is thought to measure the flicker perception threshold that changes according to the excitability of the central nervous system including the brain cortex or the change in the level of arousal due to accumulation of fatigue. Since there are personal differences in CFFs, it is reasonable to measure CFF of the subject at a normal state, and to determine the fatigue condition at a given time based on "how much the measured CFF changed compared to the normal condition." For example, caution must be issued when CFF is decreased 5 % compared to the normal state, or one must take a break if it decreases 10 % or more. According to the previous research, in the case where CFF decreases 10 % or more, it is known that the cognitive and behavioral performance degrades significantly as represented by the worsening of scores on a simple math test.[14]

Major technological issue when conducting the flicker test using personal computers and smartphones is "how to measure the flicker perception threshold using the display of general-purpose electronic devices." In the conventional flicker test, LED is used to gradually change the flashing frequency of visual stimulus by 0.1 Hz units to determine the threshold at which the subject perceives the flickering sensation. On the other hand, for the display screen of smartphones or PCs, the vertical synchronizing frequency (refresh rate) is fixed at a certain value (15 or 30 Hz with typical cell phone displays; 60 Hz with PCs), and the flashing frequency cannot be controlled at 0.1 Hz accuracy. Therefore, it is necessary to develop a method to evaluate the flicker perception threshold that is compatible with CFF but not dependent on the changes in the flashing frequency of visual stimulus.

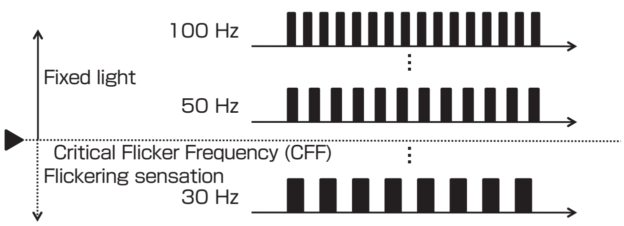

Fig. 1 Critical flicker frequency (CFF)

Also, in the conventional flicker test, the method of limit, where the flashing frequency is gradually and continuously changed at certain intervals and the subject is asked to push a button at a point when he/she subjectively perceives the flickering, is used to determine the frequency threshold of the flicker perception. With this method, it is difficult to remove the contamination from habituation and expectation as one takes the flicker test repeatedly, as well as the bias from subject's arbitrariness or intention to manipulate the results. These issues had not been critical problems in conventional use such as in a laboratory setting where the examiner and the subjects sat face-to-face while collecting the data, and thereby it had been possible to maintain the subject's motivation for accurate data measurement. However, in the case of measuring the flicker perception threshold autonomously without an examiner in daily life, avoiding the bias from arbitrary operation by the examinee during measurement becomes an issue that must be taken into serious consideration.

We developed techniques to bring the reliable fatigue measurement method based on the flicker perception threshold, which is originally used for academic research in the laboratory setting, to our daily life. We also constructed a prototype system by integrating the elemental technologies, and conducted fatigue evaluation experiments in the real environment to verify the effectiveness of our approach.

3 Elemental technologies to realize a simple fatigue measurement system that can be used daily

As mentioned above, to realize the quantitative evaluation of mental fatigue in the daily environment by flicker perception threshold measurement that has been used for research in a lab setting, it is mandatory to solve the following technological issues:

(a) To develop the elemental technology that allows the measurement of flicker perception threshold, which was measurable only on specialized devices, to be made on general-purpose display devices.

At the same time, it is necessary to deal with new issues that may arise in the course of transferring the fatigue measurement from laboratory setting to our daily environment. Particularly, the following technology needs to be developed to realize the fatigue measurement in our daily life:

(b) To develop a mechanism that allows users to conduct the test autonomously, that is, to develop the elemental technology that allows the measurement of flicker perception threshold, which was originally dependent on the subjective reporting of the examinee under the supervision of the examiner, in an objective manner even by the user alone.

3.1 Measurement of flicker perception threshold using the general-purpose display: Contrast-controlled flicker stimuli (CCFS)

First, we developed a technique to allow the CFF measurement on general-purpose display devices, based on the previous research that there is a systematic relationship between the flicker perception threshold in the flashing frequency and the brightness contrast (a difference in brightness between ON and OFF of the flashing light stimuli).[15][16] Figure 2 shows the relationship between the flashing frequency and the brightness contrast at which the observer perceives a flickering sensation (flicker perception threshold: FPT). (edited based on References [15] and [16]). The FPT is affected by changes in both the flashing frequency and the brightness contrast. When the measurement value in normal conditions is the black line, it changes to the grey line in conditions of fatigue (Fig. 2). This means that under the same brightness contrast, flicker is readily perceived as the flashing frequency decreases, and under the same flashing frequency, flickering is readily perceived as the brightness contrast increases. In the conventional flicker test, the frequency at which the subject perceived the flicker (CFF) was measured under the constant brightness contrast. In contrast, the change of FPT due to fatigue can be also characterized by using the brightness contrast threshold under the constant flashing frequency. Using this characteristic, it is possible to measure the change of FPT due to fatigue in an image display device with fixed refresh rate.

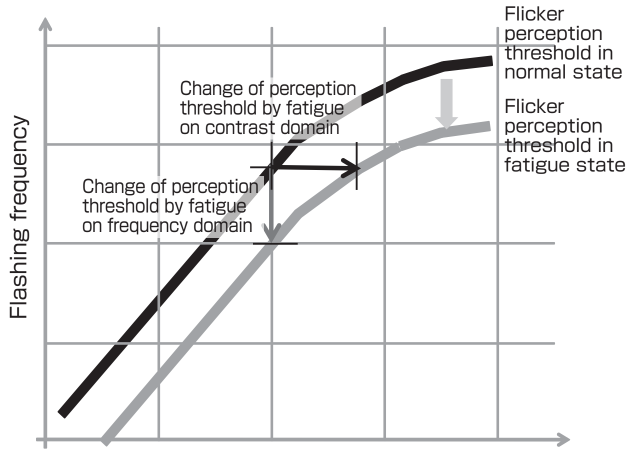

Fig. 2 Relationship between the flashing frequency and ON/OFF brightness contrast in the flicker perception

We devised the contrast-controlled flicker stimulus (CCFS) method[17] that allows fatigue measurement with accuracy equivalent to the conventional flicker test, by changing the brightness contrast between high (ON) and low brightness (OFF) of the flashing visual stimuli, rather than changing the flashing frequency as in the conventional flicker test. Figure 3 shows the measurement results of the state of mental fatigue accumulation as the subject engages in the office work such as creating materials on a computer from 14:30 to 8:30 the next day, using: (i) the CCFS implemented on a cell phone with display of refresh rate of 30 Hz; (ii) the CCFS implemented on a personal computer with display of refresh rate of 60 Hz; and (iii) the specialized device (RDF-1, Sibata Scientific Technology Ltd.) for conventional flicker test (average of 12 subjects; error bar represents the standard deviation). In all methods, accumulation of mental fatigue due to the overnight work and the recovery of fatigue by short naps were appropriately measured as in the conventional flicker test. It was also found that the results obtained by CCFS flicker test were significantly correlated with the test results of the conventional flicker test (Fig. 4).

These results show that the FPT measurements by CCFS implemented on the widely available consumer devices can be used as an alternative to the original flicker test which requires the specialized device in evaluating the progressive

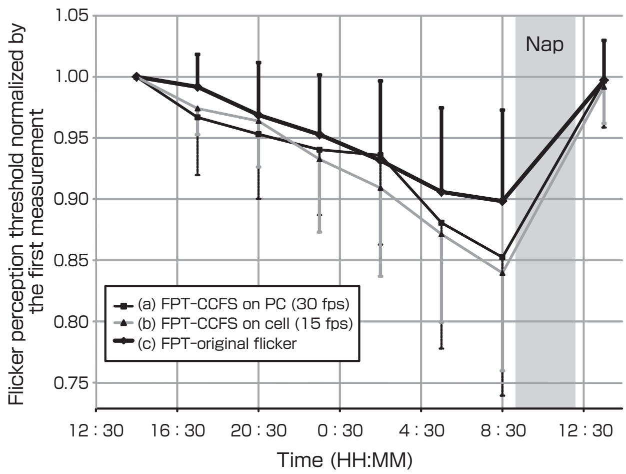

Fig. 3 Results of the fatigue measurement under overnight workload[17]

Measurements conducted by contrast-controlled flicker stimuli (CCFS) application implemented on a cell phone (thin grey line) and a PC (thin black line), and by a specialized device for conventional flicker test (thick line).

development of fatigue due to overnight mental workload.

3.2 Autonomous measurement of flicker perception threshold without the examiner

In the conventional flicker test, the method of limits is used where the flashing frequency is gradually and continuously changed at fixed intervals and the subjects are asked to respond by pushing the button at the moment he/she subjectively perceives the flickering sensation, and it is difficult to eliminate the contamination from biases including the subject's arbitrariness in responding to the perception of flickering sensation. This has not been a major problem as far as the method was used in the laboratory setting where the examiner and examinee sat face-to-face during data collection, hence the examiner could intervene as needed to avoid the possibility of the contamination. On the other hand, it is going to be an important issue to be solved when the method is applied to the measurement of flicker perception threshold in daily life where the examinee has to conduct the test autonomously without an examiner.

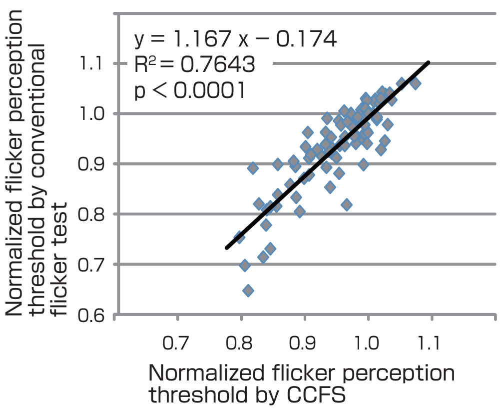

Fig. 4 Correlation between the flicker perception threshold measured using the contrast-controlled flicker stimuli (CCFS) and the conventional frequency-controlled flicker stimuli[17]

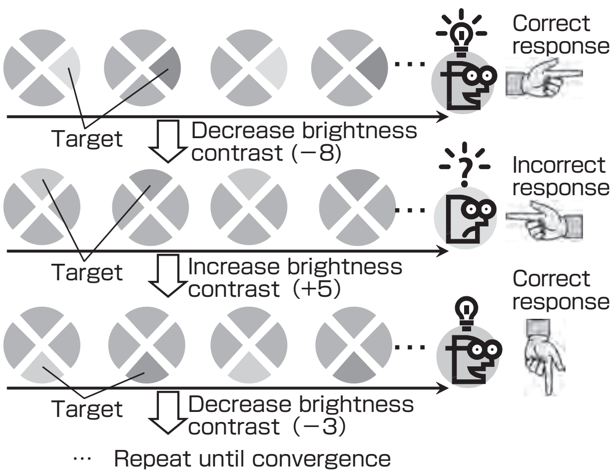

Fig. 5 Schematic diagram for the method of determining the flicker perception threshold by the forced-choice up/down (FCUD) method

To solve this issue, we introduced the forced-choice up/down (FCUD) method which adjust the stimulus parameter, brightness contrast in this case, adaptively corresponding to the subject's response so that the parameter converges to the flicker perception threshold.[17] Specifically, as shown in the schematic diagram of Fig. 5, the subject is required to choose a flickering target stimulus among the multiple stimuli presented. If the subject's reaction is correct, i.e., the subject chooses the flickering target stimulus which is randomly placed among other stationary alternatives, the brightness contrast of the target stimulus is decreased in the next trial to make the forced-choice task more difficult. Otherwise, the brightness contrast of the target is increased in the next trial until the subject can make a right choice. These steps are repeated until the brightness contrast is converged to the flicker perception threshold.

The accuracy of the flicker perception threshold measurement can be improved by using FCUD algorithm since it allows denser sampling around the perception threshold compared to the original flicker test where the brightness contrast is changed at a constant rate regardless of the subject's response (Fig. 6). The FCUD also contributes to reduce the amount of time required to complete the test by accelerating the convergence at the brightness contrast range where the flickering is less likely to be perceived (Fig. 6).

4 Integration of technologies for fatigue measurement in daily life

To verify the effectiveness of the techniques described in subchapters 3.1 and 3.2 to be used for the fatigue measurement in daily life, we created a prototype system combined with an online database to manage the measured

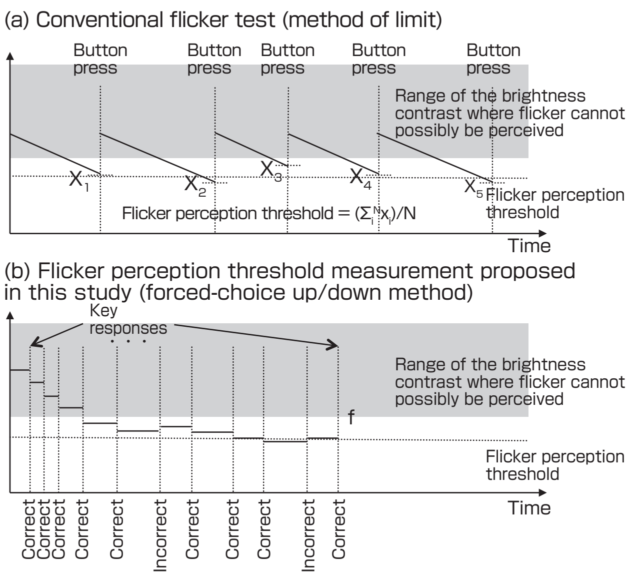

Fig. 6 Differences in the methods for determining the flicker perception threshold in the conventional and the proposed methods

data (Fig. 7). This system accomplished the following:

(i) The CCFS (subchapter 3.1) enabled the presentation and control of flickering visual stimuli on the general-purpose display device,
(ii) The FCUD-FPT algorithm (subchapter 3.2), which eliminates the subject's arbitrariness in measuring the flicker perception threshold, is implemented to enable appropriate fatigue measurement without the attendance of the examiner. It also contributes to reducing the overall time required to complete the test, and
(iii) Online database was built to manage the measured data, where the fatigue data can be registered and referenced as needed from the application software installed on the terminal devices such as smart phones and PCs (Fig. 7).

We conducted actual trials on truck drivers in collaboration with transportation companies that are expected to be our potential users of the system. In the trial, the fatigue measurement was included as part of a dairy routine at the beginning and the end of work. Interview to the safety managers showed that reducing the time needed for testing to less than one minute was a critical factor in its implementation. Therefore, we achieved this goal by reviewing the convergence parameter of the FCUD-FPT algorithm. In the prototype system that was implemented on the personal computer, the time required for measurement was reduced to as short as 40 seconds compared to about 70 seconds with the conventional flicker test (Fig. 8).

5 Effect of realized outcome and new research topics

We have developed a set of techniques to bring the flicker test, which has been originally used to measure mental fatigue in the laboratory setting using specialized devices, into our dairy life. We confirmed that the results obtained by our method, which is a combination of the CCFS and the FCUD-FPT algorithm, are compatible with those measured by the conventional flicker test. Our prototype system is being used for the long-term data acquisition trial in the business environment including two medium-sized transportation companies and in the R&D division of a major construction company. The above technology is also being commercialized by Flicker Health Management Co., Ltd. (FHM), an AIST Start-up (a venture company aiming to commercialize the AIST research outcomes).[18] Currently, the system is being used mainly to study the continuous changes in fatigue condition, which are originally measured by the conventional flicker test using specialized devices, at R&D division of information appliances companies, automobile companies, and university laboratories. The FHM also distributes free apps with simplified functions and operation for smart phones to be used by the general public, to promote diffusion of the fatigue evaluation technology in daily environment.[19][20]

Originally, the flicker test has a long history as a fatigue measurement method for academic purposes at research institutes, and it was used to evaluate the change of fatigue conditions in the time span of several hours to several tens of hours. The results of our research and development on the fatigue measurement provides low-cost alternative to the original flicker test, which has an established reputation for its robustness in tracking the changes of fatigue condition, using readily available devices. This allows not only the easy monitoring of the changes in fatigue condition in short periods that was done conventionally in laboratories, but also allows the continuous measurement over a long term of the daily changes in the degree of fatigue. These techniques can be applied to long-term monitoring of fatigue over a large subject population. There is no precedent research on

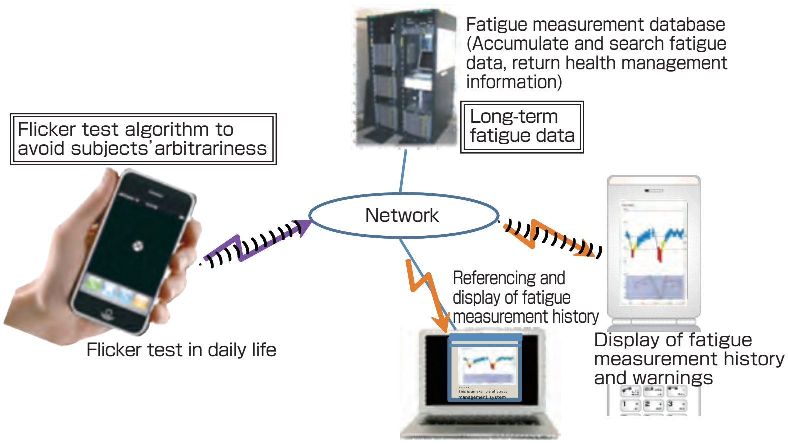

Fig. 7 Prototype system of the mental fatigue measurement and management system that can be used in daily life

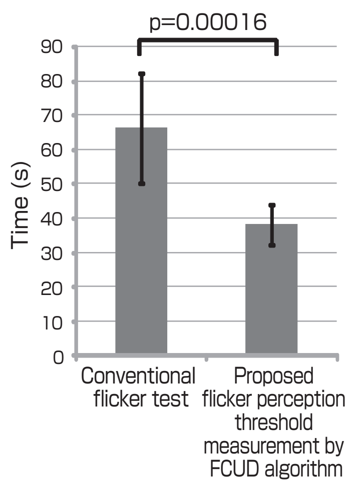

Fig. 8 Comparison of time required for flicker perception threshold measurement by the conventional method and the FCUD method[17]

quantitative evaluation of the chronic changes in fatigue. While it is not certain what kind of information can be extracted from the chronic fatigue data that are measured daily and continuously, it may be possible to use this technology effectively in various scenes in our society from health management at a personal level and improvement of our living environment to optimization of resource distribution and task efficiency in companies, based on the temporal change of mental fatigue conditions. We are starting to collect data to clarify the significance of conducting fatigue measurement continuously over a long term in the real living environment. Figure 9 shows an example where an engineer who works at a R&D division of a private company continuously measured the flicker perception threshold for five weeks including the summer vacation period using the Android smart phone app that we developed. While this is still in the preliminary stage, we are obtaining results that the changes in the daily fatigue level are related to the work and off-day patterns.

6 Summary and future development

We developed a low-cost, practical mental fatigue monitoring system to be used in daily life based on the measurement of flicker perception threshold (flicker test) which has been used conventionally for academic purposes in a laboratory setting. Our prototype system showed promise in implementing such a system just by installing the software in the general purpose personal devices, e.g. smart phones and PCs, which are readily available in daily life.

The remaining issue is to deal with the dependency of the flicker perception threshold on the changes in surrounding lighting environment and visual distance. Although the basic idea has been submitted for correcting the measurement result based on the lighting condition and visual distance using the camera function installed in the device (Japanese Patent # 4406705), verification based on real data has not yet been done. For now, we instruct the users to conduct measurement under the same lighting and viewing conditions as much as possible, however, it is necessary to develop an additional technique for robust fatigue measurement in changing surrounding environments for further diffusion.

The flicker perception threshold is also affected by age and eyesight of the user as well as the display performance of the information device. In the laboratory setting, the variation by examinees can be standardized by using the results of the reference measurements conducted at the start of the experiment or before applying workload (standard value), but it is expected that the standard value cannot be obtained accurately for continuous measurements in daily life. We are developing an algorithm to determine the standard value appropriately from the previously acquired data.

For the future application of the proposed technique to the screening of fatigue related diseases as well as for multifaceted understanding of mental fatigue conditions, it is also necessary to clarify the correlation between FPT and the biochemical indices such as the changes in various biomarkers obtained from blood or saliva samples. We are working with the Health Research Institute, AIST to collect blood and saliva samples simultaneously as the flicker test during overnight work load. The current results indicate that there is a significant correlation between the changes in FPT and the oxidative stress marker in the blood samples.[21]

Since there have not been any methods to evaluate long-term changes in fatigue condition quantitatively in daily life, it is not certain what information is embedded in the fatigue data acquired over several months or years. The future topics include the development of a health management system that combines our fatigue measurement technique and time-series data processing algorithms to extract useful healthcare information, as well as application to enhance work efficiency through appropriate management of fatigue

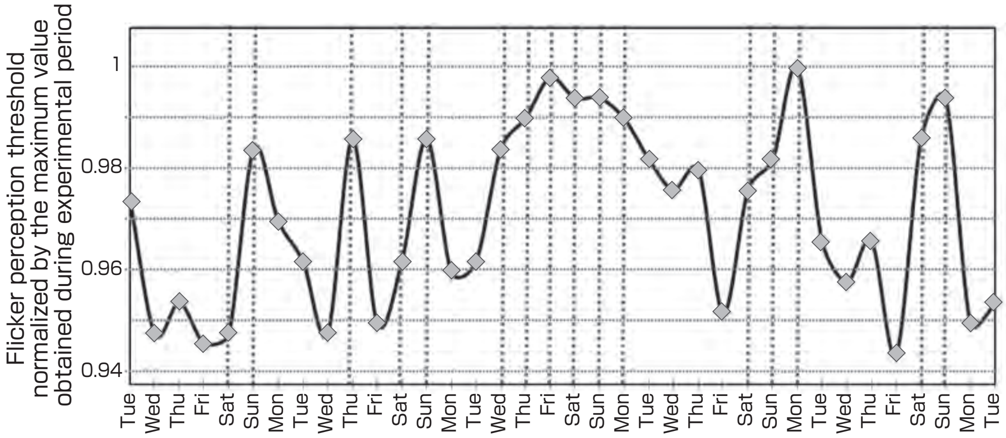

Fig. 9 Preliminary data to show relationship between changes in the flicker perception threshold and work/off-day pattern obtained by continuous measurements over five weeks for an office worker (at a R&D division of a private company). Broken lines denote off-days.

among workers. These topics are also important to enhance the range of application of this technology, and we plan to continue developing the data analysis algorithms and collecting long-term data in various environments through close collaboration with industries including the venture company for technology transfer from AIST.

Acknowledgements

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Completed the doctorate course at the Graduate School of Engineering, The University of Tokyo in 1998. Ph.D. in Engineering. Joined the Electrotechnical Laboratory in 1998. Currently, Leader of Cognition and Action Research Group, Human Technology Research Institute, AIST. Professor of Collaborative Graduate Program, Graduate School of Comprehensive Human Sciences, University of Tsukuba. Engages in the development of highly accurate, non-invasive visualization of human brain activity, its application to the objective evaluation of subjective perception and cognition, and the R&D of physiological and psychological index that can be used in daily life. In this paper, was in charge of the development of measurement algorithm for flicker perception threshold without arbitrariness to implement the fatigue measurement system on the general-purpose devices that can be used in daily life, and the drafting of the paper.

Nobuyoshi HARADA

Completed the doctorate program at the Graduate School of Environmental Sciences, Hokkaido University in 1996. Ph.D. in Environmental Sciences. After serving as JST Fellow at National Institute of Biosciences and Human Technology, CREST Fellow, and NEDO Fellow, became the AIST Fellow in 2004. In 2010, became President of Flicker Health


Management Co., Ltd, a venture company that received technological transfer from AIST. Engages in research on the effect of information factors in the environment using 1/f fluctuation on brain functions, and on the business of intellectual rights of this research result and its technological diffusion. In this paper, was in charge of the verification experiment for the simple fatigue measurement system that can be used in daily life, the implementation for commercial use, and the collection of actual measurement data in real work environment.

Discussions with Reviewers

Overall comment (Motoyuki Akamatsu, AIST)

The manuscript describes the technological development that enables the users themselves to execute the flicker fatigue test, which had been used as a method of experimental fatigue measurement, in daily life, and also addresses the practical application of this technology. The scenario for the technological development describes how a technology used in academic research could now be used widely in society, and this is appropriate as a paper of *Synthesiology*.

1 Point of technological breakthrough

Comment (Motoyuki Akamatsu)

You explain one of the technological breakthrough points of using contrast instead of frequency, and I think the characteristic of this technology will become clearer if you expand more on this point. By just adding a sentence, “By utilizing the aforementioned characteristic, it is possible to measure the change in flicker perception caused by fatigue by changing the contrast, even in devices with fixed display frequency,” I think you can emphasize that this, in fact, is the breakthrough point.

Answer (Sunao Iwaki)

Based on your comment, I added two sentences that briefly explain the point of breakthrough in using the contrast threshold for flicker perception at the end of paragraph 2 of subchapter 3.1.

2 Conventional fatigue measurement

Comment: (Katsuhiko Sakaue, Environment and Safety Headquarters, AIST)

In paragraph 3 of chapter 1, it is written that it is impossible for the general users to readily use the fatigue measurement based on objective index in daily life, but you do not address the perception and cognition indices that are the main subjects of this paper. Although it is explained in the following chapters, I think you should mention them in the same rank as other objective indices in this paragraph. It can be a brief summary, but please make some additions.

Answer (Sunao Iwaki)

As you indicated, I added the descriptions on perception and cognitive indices in chapter 1.

3 Index for flicker fatigue test using this method

Question (Motoyuki Akamatsu)

The vertical axis of Fig. 9 is different from other diagrams. Is this because the index value of fatigue has been established in the flicker fatigue test using frequency, but the value to be used as the index when using contrast has not been established?

Answer (Sunao Iwaki)

In the preliminary data obtained during the continuous use of our system in daily life as shown in Fig. 9, unlike the laboratory experiment where various parameters are controlled, there is no established method for explicitly setting the “standard value” (data that serves as the basis to normalize data with large personal variance; normally the measurement value before fatigue load is set as the standard value). This time, the largest value measured during the experimental period was set as the “standard value,” and the vertical axis of the graph was corrected so it will match the other graphs.

Also, a method to determine the “standard value” from the previously acquired fatigue data is thought to be an important point in practical application, and this could be a focus of future development which is being studied with the AIST venture company for technology transfer. I added paragraph 3 of chapter 3 to explain this point.