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Detection of Neural Fatigue State by Speech Analysis Using Chaos Theory

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Fatigue is a state of reduced physical activity with a distinctive feeling of discomfort and desire for rest caused by excessive physical and mental activity or illness. Until now, fatigue has been detected by listening to subjective fatigue levels or by measuring reactive oxygen species in the blood, but there is a need for a method that can immediately and easily measure fatigue. In this study, a fatigue task was created on a tablet device and administered continuously for 120 min to induce a temporary neurological state. We recorded the study participants' voices before and after the fatigue task and examined whether their neural fatigue could be detected using an analysis method based on chaos theory. The analysis showed that cerebral exponent macro (CEM) values, which indicate brain arousal, decreased significantly after the task, except in cases in which concentration on the task seemed to be insufficient.

1. Introduction

According to the Japan Society of Fatigue Science Research, fatigue is a state of reduced physical activity with a distinctive feeling of discomfort and desire for rest caused by excessive physical and mental activity or illness.(1) In today's society, where the future is uncertain due to the information revolution and severe economic recession, physical and mental illnesses due to fatigue and depression are on the rise. Sleep deprivation decreases mental activity during the day, which may induce mood swings, errors due to inattention, poor overall behavioral performance, and accidents due to falling asleep.(2) There is an increasing need for factories and transportation companies to take various measures to manage health and fatigue conditions. Evaluation of fatigue has been attempted by listening to subjective fatigue levels and by measuring levels of cortisol and catecholamine released into the bloodstream.(3,4) However, to prevent fatigue from interfering with work or causing accidents, it is desirable to be able to immediately measure the degree of fatigue, which is a dangerous state, at the time of fatigue or

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before driving, and the establishment of a simple and quick fatigue measurement method is required.

Shiomi[5] used chaos theory analysis on driver voice samples to measure the state of fatigue after long hours of truck driving, and reported that fatigue (physical fatigue and neural fatigue of the central nervous system) during long hours of driving decreases the cerebral exponent macro (CEM) value, which indicates brain arousal level. Sato *et al.*[6] used a similar technique to study the voices of subjects taking antihistamines and reported a decrease in CEM value after taking antihistamines. The analysis targets used in these studies were speech signals, and the goal was to quantify fatigue status by a noninvasive and simple means. However, it is difficult to distinguish between physical fatigue and neural fatigue due to sustained attention in fatigue experiments on truck drivers. The effect of medication on brain arousal is an essentially different situation from that of fatigue. No previous studies have focused solely on fatigue in the central nervous system, which is involved in brain function, and have analyzed the relationship between fatigue and speech signals. The purpose of this study is to analyze speech signals during central nervous system fatigue using chaos theory to clarify how the CEM values change.

2. Materials and Methods

2.1 Fatigue task

The human body sustains life activities by repeating the process of becoming fatigued when it is continuously subjected to loads and stimuli, and then recovering through rest (mainly sleep) commensurate with the fatigue.[7] It has also been reported that the brain's ability to maintain arousal is reduced during fatigue.[8] Kajimoto[9] created a visual search and response task on a monitor called the Advanced Trail Making Test (ATMT) as a task that evokes central nervous system fatigue, and used it in several mental fatigue tests. As a result, it was found that the number of errors and reaction time did not change significantly even after 120 min of trials. However, in a brain region exploratory study on fatigue, it was revealed that the orbitofrontal cortex, which oversees the sense of fatigue, is affected by the fatigue load caused by ATMT.[10] In this study, to induce a temporary state of central nervous system fatigue due to sustained attention rather than physical fatigue, we created a visual search task that operates on a tablet as a fatigue task, following a previous study by Kajimoto *et al.*[9] (Fig. 1). The measurement of fatigue task and fatigue should be simple, immediate, and measurable at any location, and tablet terminals are an essential part of preventive safety technology. The task was to find and tap the target number marked at the top of a tablet (iPad) with 1–30 numbers randomly placed on the tablet. The time limit was set to 10 s, and when the target number was tapped or the time limit was exceeded, the placement of the target number and the 30 numbers to be searched changed randomly. Under these conditions, the participants were instructed to "respond as quickly as possible" for 120 consecutive minutes. The number of correct responses and the number of errors (failure to respond within the time limit) were recorded. All the participants in the experiment were asked to report their introspection during the assignment after completion.

Fig. 1. (Color online) Fatigue task using tablets.

2.2 Study participants

2.2.1 Participant selection criteria

Students from Fukui Health Sciences University with no history of mental illness or cerebrovascular disorder, who can concentrate on a fatigue task until the end, participated in this study. The experiment started at 10:00 a.m. Those who had slept less than 5 h the previous day and those who had not eaten breakfast were excluded. Nineteen university students (6 males and 13 females, mean age 22.1 years, *SD* = 0.64) participated in the study as research collaborators.

2.2.2 Participant consent form

Only those who understood the content of the explanatory document and agreed to participate in the study of their own free will by signing the consent form were included.

2.3 Voice recording

2.3.1 Recording environment and format

A private room with low environmental noise was used as the voice recording room, and sound-absorbing panels were placed on the walls to reduce reverberation. The participants read aloud the text displayed on the PC screen while sitting at a desk. A headset microphone and a handheld speech microphone mounted on a microphone stand were used for multi-track recording. The sampling frequency and quantization bit rate were 48 kHz and 24 bits, respectively.

2.3.2 Speech analysis using chaos theory

Conventional speech analysis methods are based on analyzing factors such as the pitch and loudness of sound, but speech signals have very large variations, making it difficult to extract features. In addition, deep-learning-based analysis methods often have difficulty in interpreting results due to the difficulty of setting up teacher signals and the vast and varied labeling of results. As a solution to this problem, we decided to use a chaos-theory-based analysis method that can extract highly reproducible features. This is because chaos theory, a branch of mathematical physics, is a theory related to complex systems. Time series signals are discussed by reconstructing the mechanism that generates time series signals by embedding them in a multidimensional phase space (Takens' embedding theorem) and by analyzing attractors.[11] For a simple pendulum, the momentum of the weight is zero at both ends of the amplitude, and in phase space, where the position (deflection) is x and the momentum is y, the operating point of the pendulum's weight is an ellipse centered at the origin. The attractor generated by a simple pendulum is a simple ellipse. If the weight is swinging in the x direction, then $x = A \sin(\omega t + \varphi)$, and if the embedded delay time is Δt, then $y = A \sin(\omega(t - \Delta t) + \varphi)$, and (x, y) is an ellipse centered at the origin. The audio signal x is a time-series signal that can be generally described as $x = f(t)$. If the delay time is set appropriately and $y = f(t - \Delta t)$, the locus of the operating point can be drawn in two-dimensional phase space as (x, y). For the trajectory of an action point in phase space to be an attractor corresponding to the mechanism that generates its time series signal, the existence of an equivalence action point requires that the trajectory be closed there and that subsequent trajectories coincide, but if the action point in the speech signal as a time series signal is (x, y), this trajectory is not in the two-dimensional plane intersect. Therefore, it is necessary to increase the dimensionality of the phase space in which the attractor of the speech signal is reconstructed. The trajectory of (x, y) for the audio signal $x = f(t)$ with $y = f(t - \Delta t)$ is shown in Fig. 2.

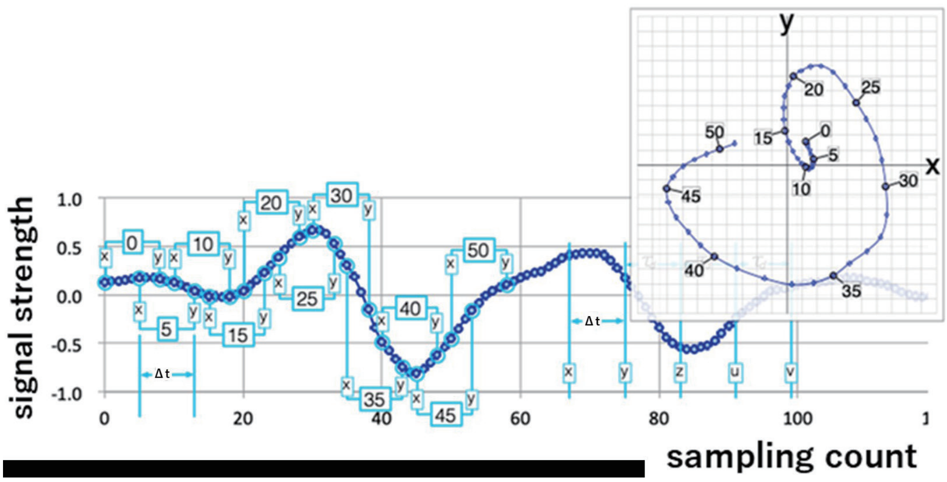

Fig. 2. (Color online) Constructing an attractor using Takens' embedding theorem.

In the case of the speech signal $x = f(t)$, it is difficult to reconstruct the attractor by embedding it in a two-dimensional phase space because the trajectories intersect. To solve this problem, embedding into a four-dimensional or larger phase space makes it possible to represent the attractors three-dimensionally even in overlapping areas, as shown in Fig. 3.

When an audio signal $x = f(t)$ is embedded in a 4D space, with a delay time of Δt, the reconstructed attractor shape changes depending on Δt as $P\,(f(t), f(t-\Delta t), f(t-2\Delta t), f(t-3\Delta t))$. If the shape of the attractor is not such that it uniformly fills the entire space, and if similar trajectories are repeated, it is judged that a valid strange attractor has been reconstructed for the analysis. In chaos-theoretic analysis methods, an object called the strange attractor can be depicted by replacing the digitized speech signal with a multidimensional phase space. It has been shown that the fluctuations of the strange attractor decrease when fatigue occurs after a long period of work or when arousal decreases after taking sleep-inducing drugs, as shown in Fig. 4.(12–15)

It is necessary to quantify the attractor to evaluate the degree of fatigue, and the maximum Lyapunov exponent is calculated using the algorithm proposed by Sano and Sawada after transforming the observed time series to time-delayed coordinates using Takens' embedding theorem.(16) By using the analysis method devised by Shiomi(17) on the obtained numbers, we calculated the CEM value, which is an index of cerebral arousal.

All the participants were asked to read aloud the 35 sentences described below before and after performing the fatigue task, and the audio recordings were made during the reading. The CEM values were calculated for each sentence, and the average value of the 35 sentences was used as the individual CEM value.

2.4 Reading texts

The participants were asked to recite a common text (35 sentences) in a voice recording environment set under certain conditions, and voice recordings of their speech were made. The texts were written in Japanese mixed with kanji and kana, with no sentences that evoked

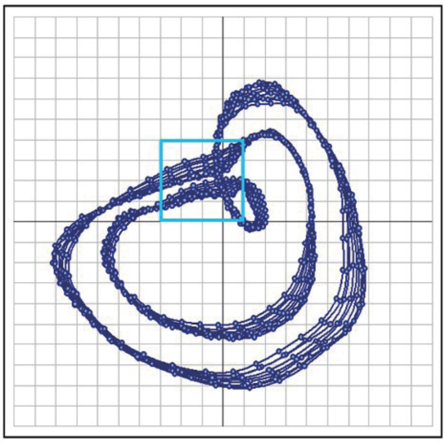

Fig. 3. (Color online) Strange attractor.

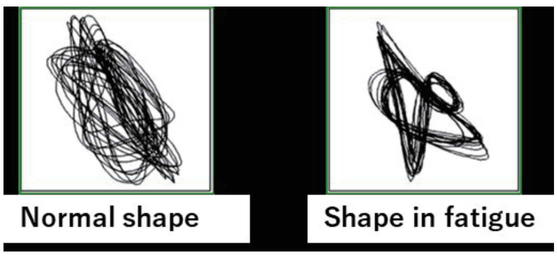

Fig. 4. Strange attractor changes due to fatigue.

emotions, and kana was added to indicate the pronunciation of kanji. The sentences were displayed one by one on a PC monitor screen, and all the participants read the sentences aloud in the same order.

2.5 Statistical processing

CEM values vary slightly from person to person. In this study, the CEM values analyzed from an individual's pre- and post-recorded speech before and after the fatigue task were compared. The CEM values were calculated for each of the 35 recorded sentences, and the average of the 35 sentences was used as the individual's CEM value. A t-test (paired t-test) was used to examine differences in CEM values before and immediately after the task at the 5% level of significance.

2.6 Ethical consideration

Since this study handles personal information regarding voice data samples, basic participant information, and clinical rating scales, it is necessary to strictly manage the information obtained during the study. Documented records were kept in a lockable cabinet by the principal investigator and destroyed by shredding thereafter.

We complied with the "Declaration of Helsinki" and the "Ethical Guidelines for Medical Research Involving Human Subjects". This study was approved by the Nittazuka Medical Welfare Center Ethics Review Committee (ethics examination number: Shinrin 20121-31). We explained the study to the participants in writing and verbally and obtained their consent. The authors declare no conflict of interest.

3. Results

3.1 Individual CEM values

In 15 of the 19 participants, the CEM values showed a significant decrease after the fatigue task compared with the CEM values before the experiment (Fig. 5).

3.2 Number of errors

Concerning the number of errors in the fatigue task (number of time-overs), the number of errors was higher in the four participants (non-fatigue group) whose CEM values did not decrease after the fatigue task (Fig. 6) than in the 15 participants (fatigue group) whose CEM values decreased after the fatigue task. Only these four participants indicated in the post-fatigue task interview that they had dozed off in the middle of the task. Therefore, they took a break during the task and could not be said to have been sufficiently fatigued.

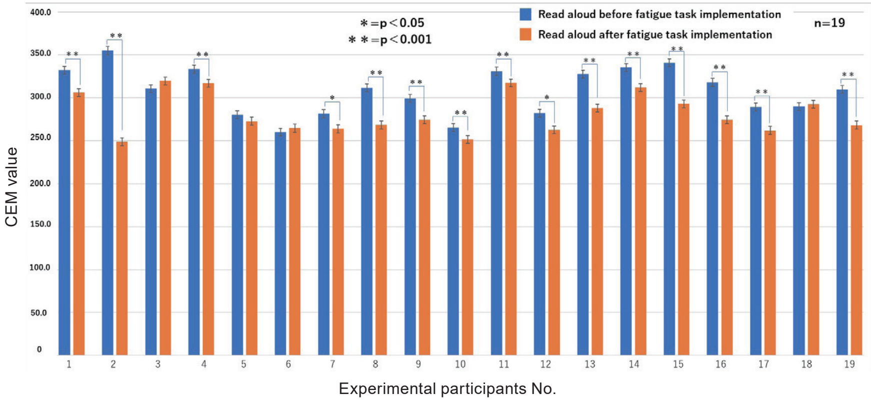

Fig. 5. (Color online) CEM values before and after fatigue task.

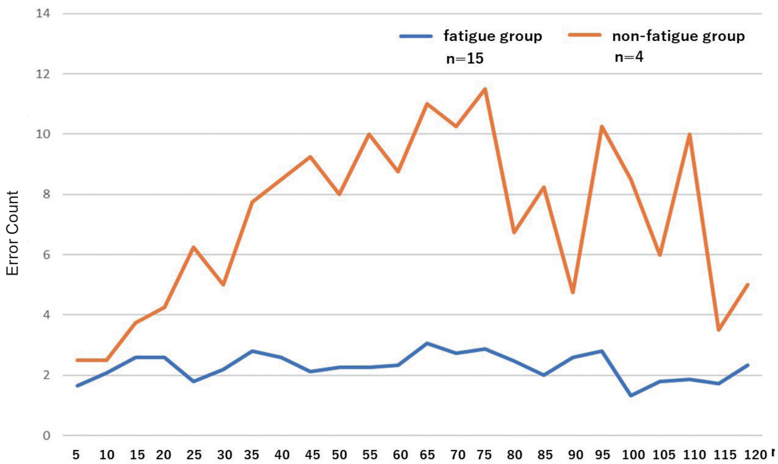

Fig. 6. (Color online) Moving average of number of errors per 5 min.

4. Discussion

In the fatigue group, it was confirmed that the CEM value analyzed from the voice recorded after the fatigue task was significantly decreased. It has been reported that the CEM value decreases when fatigue occurs due to long working hours.[17] As it has been reported that visual search tasks can cause acute or chronic fatigue with decreased attentional allocation after a relatively prolonged load,[18] the visual search task on the tablet set up in this study was performed under the condition of "search as fast as possible" for 120 min, and it was considered that the prolonged and sustained stimulation caused a temporary state of central nervous system fatigue.

Brain injury and neurotransmitter problems can cause functional decline due to the brain's inability to recover from fatigue.[19] Studies on brain function and performance have shown that central fatigue not only limits cardiopulmonary function but also reduces muscle performance,[20] and that exercise performance is impaired even in patients with brain lesions without motor paralysis.[21] The fatigue state of the central nervous system simplifies the brain network and causes performance changes in brain-derived motor commands and cognitive systems. In this study, a fatigue task created as an application on a tablet device was performed continuously for 120 min to induce a state of temporary central nervous system fatigue through repeated stimulation of searching for numbers and tapping buttons. It is usually difficult to detect such changes by ear, and it is difficult to identify the state of mind and body by looking only at the parameters of sound pitch and intensity. Therefore, it has been difficult to quantify the state of fatigue, and subjective fatigue has been studied through interviews and time-consuming biochemical tests. In this study, it was shown that it is possible to easily and noninvasively quantify and visualize the state of "tiredness" in a short time from voice signals that have been judged to be random noise, and it is a practical analysis method as an evaluation index of daily health status.

5. Future Issues

In this study, the measurement of CEM values was limited to before and after the task, but in the future, it will be necessary to measure CEM values during the process from fatigue to recovery. Although all the participants in this study were given a uniform start time for the experiment, it is necessary to clarify the relationship between the circadian rhythm and the physiological rhythm formation of the same person. The non-fatigue group with the highest number of errors in the fatigue task did not show any change in CEM values after the fatigue task. The extreme concentration of errors, especially in the middle of the task execution, may have been due to the fact that the task was a simple visual search, which induced drowsiness in the participants and caused them to become sleepy. It is considered that the CEM value did not decrease because the participants took a moderate break during the task. There is room for further study on the setting of the trial environment in terms of measuring autonomic responses during the trial of the fatigue task to measure the relationship with other measures of fatigue and on examining the index of fatigue from the analysis of movements by image recording. Although this study was conducted in a soundproof room with relatively large recording equipment, we believe that, if it becomes possible in the future to measure health status in any environment in a short time and in a simple manner, it will help reduce human errors during work due to fatigue and prevent accidents involving long-distance drivers.

6. Conclusions

It was possible to create a state of temporary central nervous system fatigue by performing a task continuously in a sufficiently focused state. Chaos theory analysis of the speech signal in the fatigued state showed a decrease in CEM values, except for the participants who appeared to be insufficiently focused on the task. The CEM value is considered to be a useful index of human arousal state, and in the future, we would like to apply it clinically to cases in which brain function is impaired due to brain disease or depression and to establish an index as a stress response.

Acknowledgments

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