The Process of Occurrence and Recovery of Psychological and Physiological Fatigue by Sleep Deprivation for Fifty Hours in Man

Kazuyoshi SAKAMOTO1), Kunihiro SEKI2), and Tositomo USUI1)

1) Department of Industrial Management Engineering, Faculty of Electro-Communications, The University of Electro-Communications, 1-5-1, Chofu-oka, Chofu-Shi, Tokyo 182, Japan
2) Undersea Physiological Laboratory, Japan Marine Science and Technology Center, 2-15, Natsushima-Cho, Yokosuka-Shi 237, Japan

The experiment of 50 hours sleep deprivation for 4 males aged 21 to 22 years was performed for a week including one adaptation day, two baseline days, and two recovery days, the load during all the awakening times being mah-jong. Physiological parameters, performance, and questionnaires were studied. During the sleep deprivation, the sequence of the occurrence of large change for the parameters was found to be the order of subjective fatigue feelings, the performance (optical choice reaction time and critical flicker fusion frequency), and heart rate. The influence to the sleep showed that the slow wave sleep and REM sleep played the important role in the first and the second recovery day, respectively.

INTRODUCTION

The sleep deprivation (SD) or sleep loss has been studied in order to evaluate the influence of physiological parameters, performance, and psychological factors on the circadian rhythm, the sleep, and the exercise. The review before 1962 was given already by Kleitman (1963). The main papers about the sleep deprivation after 1960 were summarized here. In many studies, the sleep deprivation term of two nights or for 64 hours or so was generally employed.

Physiological parameters were treated by many authors. Berger and Oswald (108 hr. SD, 1962), Williams et al. (64 hr. SD, 1964), Moses et al. (64 hr. SD, 1975), and Borbély et al. (40.5 hr. SD, 1981) studied the influence of sleep times in various sleep stages at recovery nights. Nakazawa et al. (one night SD, 1975 and 1978) and Moses et al. (1975) employed the method of partial selective sleep deprivation of sleep stages 4 and REM. They also examined the effect of the procedure on the sleep at recovery night. Naitoh et al. (64 hr. SD, 1971) showed the contingent negative variation which was surface negative slow potential in human brain. The physiological parameters treated except for electroencephalogram (EEG) were heart rate (HR) by Corcoran (60 hr. SD, 1964) and Saito (48 hr. SD, 1972), blood pressure and hormone like catecholine by Ahnve et al. (64 hr. SD, 1981), body temperature by Åkerstedt et al. (64 hr. SD, 1979), and O2 uptake (V̇O2) and ventilation (V̇E) by Martine and Gaddis (30 hr. SD, 1981). These parameters were chiefly used to investigate the effect of sleep deprivation on circadian rhythm or exercise in recovery days.

The effect of sleep deprivation on performance was studied by several authors. Harris (60 hr. SD, 1960) examined the perceptual and motor function, and Corcoran (60 hr. SD, 1964) dealt with vigilance task. Saito (48 hr. SD, 1972) used critical flicker fusion frequency (CFF). Hord et al. (two nights SD, 1975) treated various task like counting and perceptual discrimination.

The questionnaire during sleep deprivation was examined by Saito (1972), Hord et al. (1975), and Åkerstedt et al. (1979). Saito and Åkerstedt et al. examined subjective fatigue feelings. Hord et al.
studied mood test which was the anxiety test made by Spielberger (1970).

As shown above, many authors treated some of three categories of physiological parameters, performance, and questionnaire. However, there were no papers which included all three categories and studied the relationship between them, except for Saito's paper. Saito (1972) found the close relationship among HR, CFF, and subjective fatigue feelings by the use of factor analysis, but he did not considered the qualitative change of sleep by EEG study. There were no papers which studied many physiological parameters polygraphically, as far as authors knew. Moreover, many papers did not mention the sequential appearance of the change of parameters taken in three categories. Although the degree of effect of sleep deprivation on the three categories depends on many factors, that is, beginning time, period, kind of load (play, sports, task), and motivation for the load, the order of the appearance of the fatigue detected by various parameters was not necessarily found clearly. Therefore, the present purpose is to study the order of occurrence of psychological and physiological fatigue by sleep deprivation which is good procedure producing fatigue in laboratory and to detect the effective parameters for the load of sleep deprivation.

METHODS

The experiment of sleep deprivation was planned for 64 hours at first. Subjects, however, could not continue the sleep deprivation till the scheduled period, so that the experiment had to come to an end at 50 hours sleep deprivation and they had to sleep for the daytime (11:00-19:00) in the recovery days: That is, day and night were inverse for the subjects. The experiment was performed for a week with one adaptation day, two baseline days, 50 hours sleep deprivation, and two recovery days as shown in the schedule of Fig. 1. The experiment was done in summer. Subjects were four males, whose age, stature, and weight were 21.7±0.4 year, 166.5±5.1cm, and 58.40±10.15 Kg, respectively. They played mah-jong as the load during all the awakening times. Subjects slept on the bed in the chamber which cut off from outer noise and was air-conditioned as the room temperature was 23±1.0°C and the humidity was 60±5%. Subject sleep time was set to be 8 hours (0:00-8:00AM).

The parameters measured consisted of three categories, that is. (A) physiological parameters, (B) performance, and (C) questionnaire (or subjective symptom test). (A) Physiological parameters were (a) body weight, (b) body temperature at forehead and rectum, (c) HR, (d) respiratory rate (RR), (e) respiratory parameters including oxygen uptake and carbon dioxide production, and (f) EEG. (B) Variables of performance were (g) optical choice reaction time (CRT) and (h) CFF. (c) Questionnaire was (i) subjective fatigue feelings with thirty items, (j) subjective fatigue feelings with nine stages, and

![Fig. 1. Time schedule for experiment of 50 hours sleep deprivation. The marks * and † mean the start and the end of the experiment. ][, ][, ][ denote sleep time, awakening time (playing mah-jong, measurement of parameters, meal, and toilet), and sleep deprivation (playing mah-jong).]
(k) local physical fatigue. During the awakening, (A) parameters except for (a) and (e) were measured continuously, while all the other parameters ((a), (e), and (g)-(k)) were measured at each four hours. The measurement time including meal or toilet was thirty minutes. The order of the measurement was (C), (B), and (A). During the sleeping, only (A) parameters except for (a) and (e) were measured continuously.

The parameter (a) was measured by digital platform scale (Type DBS-1040, (Shinko Denshi)), and the parameters (b) and (d) were detected by temperature and respiratory sensor (Type 706 and thermistor, (Takara Kogyo)). (c) HR was evaluated from electrocardiogram at chest, using EEG apparatuses (Type 4113, (Nihon Koden) and Type 1A58 sp, (Sanel Sokki)). In (e), O₂ uptake and CO₂ production (\( \dot{V}_{\text{CO}_2} \)) in the resting state were evaluated for the expired air for five minutes by Douglas bag method (Type 1100, (Perkin Elmer)). In (f), EEG by bipolar leads of \( F_{\gamma} - C_{\zeta} \) and \( T_{\gamma} - O_\zeta \), EOG between right and left canthus, and EMG at m. mentalis were measured polygraphically by the use of the above EEG apparatuses, where EOG and EMG were used for the detection of REM (Aserinsky and Kleitman, 1953). From these results, (f) sleep stages were evaluated on the basis of the criterion of Rechtscha-ffen and Kales (1968). The percentage of sleep stages and wake time for each day was evaluated here on the basis of actual total sleep time. The actual total sleep time was generally shorter than the total sleep time set (i.e., 8 hours), because the wake time was included for the total sleep time set. Therefore, the sum of the percentage of all the sleep stages and awake was usually larger than one hundred percents. EEG was also used to detect microsleep during sleep deprivation. If the microsleep for any subject was found, he was required to continue the sleep deprivation. As for (B) performance, (g) CRT was obtained by one selection of three colored switches with the use of apparatus of whole body reaction (Type II, (Takei Kogyo)). Ten signals for each switch was given optically. The values of CRT between 0.2 and 2.0 sec were used as right reaction. The average of three times measurements for both upward and downward series was obtained in (h) CFF, using Flicker apparatus (Type FL-10, (Shibata Kagakukan Kogyo)). The procedure for questionnaire was as follows. (i) Subjective fatigue feelings consisting of thirty items made by Japan Industrial Hygiene Society (Saito et al., 1970) was used. For the parameters of (i) and (j) entered at each four hours, the mean values were evaluated by percentage. As for (k), subjects marked the local fatigue parts in the front and the rear figure of body. The sum of the marks of all the subjects was counted.

RESULTS

1. Parameters which were not influenced during sleep deprivation.

The change of (a) body weight in the baseline days showed that the weight increased monotonously by at most 4.0% after subject's rising time as shown in Fig. 2, but the difference between the value at the rising time and the value at going to bed was not significant by the t-test for paired data. During

![Fig. 2. Body weight. (mean ± standard deviation). As for A1, B1, and R1 etc., see Fig. 1. Body weights for respective subjects at the time of rising (i.e., 8:00AM) in the first baseline day were taken as standard values, that is, one hundred percent, where the standard body weights for subjects A, B, C, and D were 65.52, 70.14, 53.81, and 44.18 (Kg), respectively.](image-url)
sleep deprivation, the decrease of the weight showed no uniform tendency, and the change was not recognized statistically. The weight at the rising time at first recovery day was larger by about 1.1% than that at the first baseline day, but both values were not significant by the t-test for the paired data. The weight curve for recovery day showed the same change as the curve for baseline days. Although the day and the night were inverse at the recovery days (see Fig. 1), the curve presented the similar circadian rhythm in the baseline days. The influence of sleep deprivation on the body weight was not recognized.

The circadian rhythm of rectal temperature during sleep deprivation was found. The difference between the maximum and the minimum temperature in a daytime was small to be 1.2°C. It was reported that the temperature at early morning which gave the lowest value in a day decreased as the sleep deprivation progressed (Kleitman, 1963, pp. 227), but the tendency was not recognized in the present study as shown in Fig. 3. In the recovery days, the rectal temperature showed the individual difference. The skin temperature of forehead did not present the uniform tendency. The effect of sleep deprivation on body temperature was not necessarily recognized clearly.

The value of respiratory rate during sleep deprivation showed almost constant value, which was different for respective subjects (vide infra). The parameter $\dot{V}_{\text{co}_2}$ for the resting state presented the distinct circadian rhythm both during sleep deprivation and in the recovery day as well as in the baseline days in Fig. 4 (Reilly and Brooks, 1982). The parameter $\dot{V}_{\text{co}_2}$ for the resting state showed similar tendency. Therefore, the parameters of respiration ((d) and (e)) did not denote the effect of sleep deprivation.

Fig. 3. Body temperature of rectum (R.T.) and of surface on forehead (S.T.). Subject A. As for A1, B1, and R1 etc., see Fig. 1. The hatched parts show sleeping period.
2. Parameters which were influenced during sleep deprivation.

The large change of parameters employed was shown in the order of the occurrence as follows. The first large change appeared at 16-20 hours after the beginning of sleep deprivation in the questionnaires, of which the subjective fatigue feelings was shown as one example in Fig. 5. The second large augmentation happened at 40-44 hours sleep deprivation (Fig. 5). The two turning points of 16-20 hours and 40-44 hours denoted the time of 0:00-4:00 AM. In two steps of the change, the largest augmentation was due to dull-drowsy factor called as group I (Saito et al., 1970). After 16 hours sleep deprivation, the frequency of the factor of difficulty in concentration called as group II was larger than the frequency of the factor of physical disintegration called as group III. The result meant that subjects felt much fatigued sensorially and mentally. In the first recovery day, the frequency of group I was larger than that in baseline days, but the frequency of group II became to be smaller than that of group III, so that the relation of frequency order of the groups was I > III > II. This result showed the normal case which subjects gave at usual work. In the second recovery day, subjects presented the same fatigue feelings as in the baseline days. Therefore, the effect of sleep deprivation continued till the first recovery day.

The other questionnaires of (j) subjective fatigue feelings with nine stages also gave the similar results.

At the period of 40-44 hours sleep deprivation, (g) CRT in performance also showed large increase as shown in Fig. 6: That is, the lowering of the performance was recognized. The value of CRT in the recovery days returned to the value in baseline days. Although the value of (h) CFF showed the individual difference, the tendency of the change was the same as CRT gave.

Furthermore, after 45-47 hours sleep deprivation (i.e., 5:00-7:00 AM), the value of HR as one of physiological parameter began to decrease rapidly by about ten to twenty beats per minute as compared with the value at the beginning term of sleep deprivation. This phenomenon was not explained by only the circadian rhythm. The results which the period parted by 24 hours were shown in

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**Fig. 4.** Oxygen uptake (\(V_{\text{O}_2}\)) for the resting state. (mean ± standard deviation). The oxygen uptake values for respective subjects at the time of rising (i.e., 8:00 AM) in the first baseline day were taken as standard values, that is, one hundred percent, where the standard oxygen uptake for subjects A, B, C, and D were 313.8, 283.2, 251.1, and 210.5 (mL/min.), respectively. As for A1, B1, and R1 etc., see Fig. 1.

**Fig. 5.** Subjective fatigue feelings. (mean ± standard deviation). As for A1, B1, and R1 etc., see Fig. 1. Frequency is expressed by the percentage of the total questionnaire items, which all the subjects marked, for thirty questionnaire items of four subjects (i.e., 100% equals to 120 marks).
Fig. 7, in which the value of RR was shown to be not suffered from sleep deprivation.

Subjects presented local physical fatigue at the parts around waist during sleep deprivation but their physical fatigue feelings in the recovery days transferred to shoulder parts like shoulder blade.

3. Change in content of sleep by 50 hours sleep deprivation.

The feature of the sleep in the adaptation day showed that the beginning time of sleep after subjects went to bed prolonged to be 0.5-1.0 hour for the laboratory effect, and that sleep stage REM (SREM) in the first sleep cycle did not appear and the sleep cycle became irregular. The sleep in the second baseline day returned to the normal pattern of sleep stage which the first half of sleep occupied larger proportion of slow wave sleep of sleep stages 3 and 4 (S3 and S4) and the latter half presented longer sleep time of SREM. In the recovery days, the sleep pattern was much affected by sleep deprivation. One example of sleep stages was shown in Fig. 8. The quantitative evaluation explained above results more clearly as follows. Total sleep time showed the laboratory effect in adaptation day.
and the effect of sleep deprivation in the first recovery day as shown in Fig. 9 and Fig. 10. In the first recovery day, all the subjects began to sleep from the deepest non-REM sleep stage S4 and its duration period was long to be from 45 to 85 minutes. As one particular case, it was measured that one subject did not present SREM during all the actual sleep times in the first recovery day and his sleep was occupied almost by S2 and S4. Moreover, the slow wave sleep increased with the significance of 1% as compared with the sleep in the baseline days, while SREM in the second recovery day increased with the significance of 1% but the sleep of S1 and S2 decreased with the significance of 5% as shown in Fig. 10. These statistical significance difference was found by t-test of corresponding data. The slow wave sleep was demanded in the first place after 50 hours sleep deprivation, and SREM was demanded in the next place, so that in the second recovery day, the rebound of SREM was recognized and moreover, S1 and S2 decreased for the rebound of SREM within the confined 8 hours sleep. In the second recovery day, slow wave sleep did not decrease (Fig. 10). Therefore, it was considered that the slow wave sleep was yet necessary in the second recovery day.

From all the above results of sections 3.2 and 3.3, the significant change of parameters was summarized in Table 1. The order of occurrence of effective parameters were (i) subjective fatigue feelings as questionnaires, (ii) CRT and CFF as performance, and (iii) HR as physiological parameters. The study of sleep stages was effective to detect the influence of sleep deprivation in the recovery days.

![Bar chart](image)

**Fig. 9.** Actual total sleep time. (mean + standard deviation). 100% means 8 hours. As for A1, B1, and R1 etc., see Fig. 1. Total sleep times for R1 and R2 show no significance by t-test for the corresponding data, as compared with total sleep times for B1 and B2.

![Bar chart](image)

**Fig. 10.** Awakening time and sleep time for various sleep stages. (mean + standard deviation). Actual total sleep times excluding awakening time for respective subjects denote 100%. As for A1, B1, and R1 etc., see Fig. 1. The marks * and ** mean the significance difference of 5% and 1% by t-test for the corresponding data, as compared with the mean value in two baseline nights.
Table 1. (a) Order of occurrence of the large change of parameters

<table>
<thead>
<tr>
<th>Subjective fatigue feelings</th>
<th>16-20 hr (0:00-4:00)</th>
<th>40-44 hr (0:00-4:00)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance (CRT, CFF)</td>
<td>40-44 hr (0:00-4:00)</td>
<td></td>
</tr>
<tr>
<td>Physiological response (HR)</td>
<td></td>
<td>45-47 hr (5:00-7:00)</td>
</tr>
</tbody>
</table>

The mark of hand pointing upward denotes the commencement of the period of increase of frequency required for subjective fatigue feelings, and the downward hand shows the lowering of function in performance and heart rate. Figure in parenthesis presents time in AM.

Table 1. (b) Rebound of sleep stage

<table>
<thead>
<tr>
<th>Sleep stage</th>
<th>1st. recovery day</th>
<th>2nd. recovery day</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-REM (1 + 2)</td>
<td>n.s.</td>
<td>*</td>
</tr>
<tr>
<td>non-REM (3 + 4)</td>
<td>**</td>
<td>n.s.</td>
</tr>
<tr>
<td>REM</td>
<td>n.s.</td>
<td>**</td>
</tr>
</tbody>
</table>

The upward and the downward hand show the increase and decrease of sleep time, respectively. The marks * and ** show 5% and 1% significance, respectively, as compared with the values for baseline nights, and n.s. means no significance.

DISCUSSION

The first change which occurred after 16-20 hours sleep deprivation was obtained by subjective fatigue feelings. This change preceded the change for the performance and the physiological parameters. The next change was recognized simultaneously in both the subjective fatigue feelings and the performance twenty hours later (i.e., at the period of 40-44 hours sleep deprivation). The term between the first and the second change was too long to manifest the first change as the preceding sign for physical fatigue. Since the two changes for the subjective fatigue feelings appeared at the time of 0:00-4:00AM, it was considered that the change was much affected by the circadian rhythm. The lowering of performance at 40-44 hours sleep deprivation was considered to be due to the effect of not circadian rhythm but sleep deprivation, because the large change was not recognized at the same time of 0:00-4:00AM in the first half of sleep deprivation (i.e., 16-20 hours sleep deprivation). Åkerstedt et al. (1979) found two periodic peak for frequency of self-rating fatigue in early morning in the experiment of 64 sleep deprivation, but such a periodicity was not obtained in the present study. As their procedure by self-rating fatigue indicated maximum score at the first large change, the monotonous increase of the frequency was not expressed in the period succeeded, while
our result showed monotonous increase as shown in Fig. 5.

The correspondence between self-rating fatigue and rectum temperature was recognized by Åkerstedt et al. (1979), but the present result could not find such a relationship. Our results revealed that the first change of the frequency for subjective fatigue feelings did not reflect the performance and physiological parameters in the period of 16-20 hours sleep deprivation as yet. Using the lighter load than ours, Corcoran showed the lowering of performance in mental and vigilance task at the period around 32 hours sleep deprivation, which time was earlier by about 8 hours than our result (Fig. 6). Harris (1960) presented the lowering of perceptual and motor function at the period of about 40 hours sleep deprivation. Saito (1972) showed the rapid increase of CRT value in the early morning at the period of about 42 hours sleep deprivation. Although the lowering period was different by the kind of load employed, the lowering of performance appeared 16-24 hours later measured from the first change of the frequency of subjective fatigue feelings. The performance of CRT and CFF returned to the normal function after the sleep in one recovery day. The same result was reported in the experiment of 48 hours sleep deprivation by Saito (1972). Such rapid recovery for the performance was not obtained for the questionnaires and the physiological parameters.

Furthermore, the rapid drop of HR appeared at the period of 45-47 hours sleep deprivation (i.e., 5:00-7:00 AM), which phenomenon was considered to be due to the influence of sleep deprivation. In general, it was known that sleep deprivation disturbed the circadian rhythm (Ahnve et al., 1981). The present result of HR did not also presented the circadian rhythm during the sleep deprivation, and the dropped value of HR by 10-20 beats per minute was too large as compared with the curve of circadian rhythm of rest state in daily life. Therefore, the depression could not be explained by the influence of only the circadian rhythm. Corcoran (1964) recognized the rapid drop of HR at the period of 48 hours sleep deprivation. He appreciated the hypothesis that sleep deprivation reduced arousal and stated that HR was valid measurement of the level of arousal. Although the load was different from ours, his result was an agreement with our results. After all, at the period around 45-47 hours, the influence of sleep deprivation on the physiological function was recognized. Saito (1972) revealed that the close relation between HR and performance like CRT and CFF. The present results did not necessarily found the relation no matter how the periods of change in both HR and the performance approached. In place of the result, the order of the occurrence of change for the parameters was found as shown in Table 1.

In recovery days, the sleep was much affected by more than 50 hours sleep deprivation as many authors showed (Berger and Oswald (1962); Williams et al. (1964); Saito (1972); Moses et al. (1975)), but the results for less than 40 hours sleep deprivation did not prove the clear effect of the sleep deprivation on the sleep (Nakazawa et al. (1975, 1978); Borbély et al. (1981)). The significant increase of both slow wave sleep in the first recovery day and REM sleep in the second recovery day was agreement with the results by Berger and Oswald (1962) and Kleitman (1963). Berger and Oswald evaluated REM rebound in the second recovery day as the phenomenon for need of dreaming. However, Moses et al. (1975) did not recognize the change of REM sleep in total sleep deprivation for two nights, whereas their partial REM sleep deprivation experiment of course showed REM rebound. According to the load and the term employed, the influence of sleep deprivation on the content of sleep, especially of REM sleep, was different. Although day and night were inverse in the recovery days, the ultradian rhythm of sleep was not affected, since the first half of sleep for the daytime of 11:00-19:00 did not increase the REM stage in the first
and the second recovery days as the REM sleep in daytime sleep showed the increase at the first half of sleep. After all, our result of sleep in 50 hours sleep deprivation found that the slow wave sleep played the most important role in the recovery term, and that the requirement of REM sleep was recognized in the second place.

**SUMMARY**

The experiment of 50 hours sleep deprivation was performed for one week accompanying with one adaptation day, two baseline days, and two recovery days. Subjects are 4 males aged 21 to 22 years. The load in all the awakening times was mah-jong. The physiological parameters employed were (a) body weight, (b) body temperature at forehead and rectum, (c) heart rate, (d) respiratory rate, (e) respiratory parameters like oxygen uptake and carbon dioxide production, and (f) sleep stages. Performance of (g) optical choice reaction time and (h) critical flicker fusion frequency were measured. Questionnaires required were (i) subjective fatigue feelings with thirty items and (j) subjective fatigue feelings with nine stages, and (k) local physical fatigue. The principal results were as follows.

[1] During 50 hours sleep deprivation, the order of the occurrence of large change for parameters measured was found. At the period of 16–20 hours sleep deprivation, subjective fatigue feelings showed the large frequency required. At the period of 40–44 hours sleep deprivation which went by 20 hours from the above first change, both the subjective fatigue feelings and the performance of optical choice reaction time and critical flicker fusion frequency showed the large change. The both periods for these changes occurred at 0:00–4:00 AM. Moreover, at the period of 45–47 hours sleep deprivation, heart rate as one of physiological parameters showed the rapid drop. The relation between effective parameters mentioned above was not evaluated. The changes after 40 hours sleep deprivation were evaluated as the effect of sleep deprivation.

In the process of recovery, the performance and HR returned to be the normal function after sleep in the first recovery day, while the effect on subjective feelings was detected till the first recovery day.

[2] The influence of the sleep deprivation on the sleep was shown in the point that the significant augmentation of slow wave sleep (sleep stages 3 and 4) was obtained in the first recovery day and that the significant rebound of REM sleep was recognized in the second recovery day. The slow wave sleep and REM sleep played an important role in the recovery of the fatigue.

**REFERENCES**


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