Visualization and evaluation of the relation between the estimated sleep satisfaction levels using nonlinear multiple regression analysis and autonomic nervous system

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Abstract: In this paper, the relation between estimated instantaneous sleep satisfaction using nonlinear multiple regression analysis and activity of the autonomic nervous system (ANS) is visualized and evaluated using the proposed scatter plot chart. We made a hypothesis and tested it such that the parasympathetic nerve activity (PNA) index representing the relaxation component rises as enhancement of the estimated instantaneous satisfaction level, and the sympathetic nerve activity index representing the stress component rises as reduction of the estimated instantaneous satisfaction level, during sleep. In the results of these experiments, when the average value per night of estimated instantaneous sleep satisfaction during sleep was level 3 or more, the number of points which are estimated satisfaction of level 3 or more, in the PNA index above the average value, was greater than that of less than level 3. It was found that the proposed method is effective for evaluating states of the ANS in sleep.

Key Words: stress evaluation, sleep satisfaction, nonlinear multiple regression analysis, estimated instantaneous sleep satisfaction, scatter plot chart

1. Introduction
In modern society, it has been recognized that it is important for maintaining health to improve quality of sleep, and expectations for deep sleep or pleasant sleep are increasing nowadays [1,2]. There are many people who are not satisfied with their quality of sleep when they are in bed and who feel low satisfaction with sleep when they wake up [3]. In order to solve these problems, evaluation of sleep satisfaction using environmental and vital data is studied in progress [4,5]. Many researchers have reported an analysis of various factors related to sleep and proposed a sleep monitoring system.
for high sleep quality. The tossing and turning play a role in adjusting humidity and temperature inside a bed [6]. Moreover, those are also reported to be conditions that affect quality of sleep [7]. For instance, it has been commercialized that smart mattresses and mattress pads adjust the temperature automatically [2]. In addition, it is important to track human vital signs of breathing and heart rates during sleep because it can help to assess the general physical health of a person [8]. Internet of things (IoT)-based unobtrusive sleep monitoring pillow that monitors breathing patterns and overall sleep quality quantifying was proposed [9].

The autonomic nervous system (ANS) can be assessed using frequency analysis of heart rate data during sleep [10–12]. When the sleep satisfaction level is high, it is presumed that the parasympathetic nerve activity (PNA) index such as high frequency (HF) representing the relaxation component rises. On the other hand, when the sleep satisfaction level is low, it is presumed that the sympathetic nerve activity (SNA) index such as low frequency (LF)/HF representing the stress component rises. There is a conventional method of showing the relation between PNA index HF and SNA index LF/HF using heart rate data [11, 12]. However, the relation between HF, LF/HF and sleep satisfaction cannot be confirmed. To prove the hypothesis, a new method is needed to confirm the relation between HF, LF/HF and sleep satisfaction. In this paper, we examine the relation between estimated sleep satisfaction from subject’s satisfaction level with 12 types of sleep parameters using nonlinear multiple regression analysis (MRA) and activity of the ANS from heart rate data during sleep. We visualize and evaluate the relation between estimated instantaneous satisfaction and ANS by means of scatter plot chart where the horizontal axis is HF, LF/HF, and the vertical axis is the estimated instantaneous sleep satisfaction level.

2. Experiment and analysis

There was only one test subject in this sleep experiment. He is a thirties male who has no underlying disease. The experiment was conducted in the form of sleeping while living as usual, and the sleep time was set according to his schedule. Valid data have been obtained for 106 nights in one year, except for days when the subject cannot experiment due to sensors malfunction, sleeping out by business trips, and poor health conditions, etc. The experiments were done after getting approval by the ethics review committee of Yamagata University.

The sensors needed for the experiment were installed in his bedroom as shown in Fig. 1. Sensors to be used in this experiment were selected by referring to parameters reported to be related to sleep evaluation in previous works [2, 7–9], for example, thermometers, hygrometers, and a barometer sensors to measure changes in temperature and humidity inside and outside the bed [2, 7]; a non-contact vital sensor to measure heart rate and respiration rate [8]; an accelerometer to monitor the
motion of head on a pillow [9]. In addition, in order to measure changes in temperature and humidity in the bed caused by the tossing and turning during sleep, temperature and humidity were measured in two places in the bed. Thermometers, hygrometers and a barometer sensor installed in/outside the bed were sent to file server via wireless microcomputer units (MCUs). An accelerometer and a non-contact vital sensor (Mio Corporation, Yokohama, Japan) which was used to obtain the heart rate and respiration rate are installed under the pillow, and over the bed, respectively. The following information was recorded in 10 seconds intervals during sleep: acceleration, temperature, humidity, atmospheric pressure, and vital signs such as heart rate and respiration. Table I describes the obtained 12 parameters. In addition, after the subject woke-up, a questionnaire was completed regarding his subjective satisfaction of sleep using a 5-level evaluation, where level 1 is the lowest sleep satisfaction and level 5 is the highest that. The subjective satisfaction of sleep was added to the analysis factors. The obtained data were averaged per night so as to correspond to the daily subjective satisfaction score.

Table I. Descriptions of parameters.

| No. | Parameter \((x_n)\) | Sensor | Position | Coefficient \(a_n\) | Coefficient \(b_n\) |
|-----|-----------------|--------|----------|---------------------|---------------------|
| 1   | Max, X          | Accelerometer | Under the pillow | 0.02334           | 0.00365           |
| 2   | Max, Y          | Accelerometer | Under the pillow | -0.02481          | -0.00379          |
| 3   | Max, Z          | Accelerometer | Under the pillow | 0.01419           | -0.00298          |
| 4   | Temperature     | MCU1    | Outside the bed | -0.00601          | 0.00090           |
| 5   | Atmosphere      | MCU1    | Outside the bed | 7.93709           | -0.00400          |
| 6   | Humidity        | MCU1    | Outside the bed | 0.42131           | -0.00345          |
| 7   | Temp1           | MCU2    | Inside the bed  | 2.69702           | -0.04743          |
| 8   | Humidity1       | MCU2    | Inside the bed  | 0.82428           | -0.00762          |
| 9   | Temp2           | MCU2    | Inside the bed  | -1.75515          | 0.03071           |
| 10  | Humidity2       | MCU2    | Inside the bed  | -0.96253          | 0.00840           |
| 11  | Heart rate      | Non-contact vital sensor | Over the bed | 15.52510          | -4.69099          |
| 12  | Respiration rate| Non-contact vital sensor | Over the bed | -1.40391          | 3.37326           |

An estimation formula which was created using the nonlinear MRA from the averaged values of 12 types of sensor data per one night because the satisfaction level is one data per one night is

\[
y = \left( \sum_{n=1}^{12} a_n x_n^2 + b_n x_n \right) + c ,
\]

where \(y, a_n, b_n, x_n\) and \(c\) are estimated value of sleep satisfaction, coefficient of parameter as shown in Table I, parameter value and a constant \(-3962.42\), respectively. Then estimated instantaneous sleep satisfaction was calculated from 12 types of sensor data collected every 10 seconds using the estimation formula. Figure 2 shows a comparison of the satisfaction recorded by the subject and averaged values of the estimated instantaneous sleep satisfaction using nonlinear MRA. Mean absolute error \((N = 106)\) of the estimation of sleep satisfaction is 0.410, which indicates the formula to be quite suitable for estimation.

In order to visualize and evaluate the relation between ANS index and estimated instantaneous sleep satisfaction levels using nonlinear MRA, frequency analysis of heart rate data, HF and LF are calculated. HF and LF components from vital sign measurements such as electrocardiograms are often used as relaxation or stress evaluation parameters for the ANS. HF which has a range of 0.15–0.4 Hz is used as a parasympathetic nervous system (PNS) evaluation parameter because the HF power spectral density (PSD) increases when the PNS is active. On the other hand, LF has a range of 0.04–0.15 Hz. The LF PSD increases when both the sympathetic nervous system (SNS) and the PNS are active. Therefore LF/HF is used as an SNS evaluation parameter. These parameters are used in the conventional HF-LF/HF scatter plot model, a method for the evaluation of biological stress, as shown in Fig. 3 [11, 12]. LF/HF and HF, which represent the SNS and PNS, are used for the vertical
and horizontal axes, respectively. The neutral state that the levels of both SNS and PNS are low is under the averaged values of LF/HF and HF such as the red dotted line, respectively. Zone 1 over the average of HF per night shows the relaxation state because the activity of the PNS is high. Zone 2 over the average of LF/HF per night shows the stress state because the activity level of the SNS is high.

The novel scatter plot chart is proposed to visualize and evaluate the relation between estimated instantaneous satisfaction and activity of ANS. Figure 4 shows the relation between HF, LF/HF and estimated instantaneous sleep satisfaction using the novel scatter plot chart. The horizontal axis is separated into two. Min-max normalization was performed with the average of HF being the Min. and maximum of HF being the Max. on the right of the horizontal axis. Using LF/HF on the left of the horizontal axis, min-max normalization was performed in the same method as on the right. The vertical axis is the estimated instantaneous sleep satisfaction. In Zone A, points are plotted when it is over the average value of HF and estimated satisfaction of level 3 or more. In Zone B, points are plotted when it is over the average value of LF/HF and estimated satisfaction of level 3 or more. In Zone C, points are plotted over the average of LF/HF and with estimated satisfaction of less than level 3. Furthermore, in Zone D, points are plotted over the average of HF and with estimated satisfaction of less than level 3. Zone 1 in Fig. 3 is plotted in Zones A and D in Fig. 4, and Zone 2 is plotted in Zones B and C. The relation between estimated instantaneous sleep satisfaction and HF, LF/HF can be confirmed with this chart. While conventional HF-LF/HF scatter plot chart as shown in Fig. 3 cannot show the relation between instantaneous sleep satisfaction and ANS, the proposed novel scatter plot chart as shown in Fig. 4 has the advantage of being able to schematize the relation of three indices.
3. Results and discussion

When the sleep satisfaction level is high, it is presumed that the PNA index HF representing the relaxation component rises. On the other hand, when the sleep satisfaction level is low, it is presumed that the SNA index LF/HF representing the stress component rises. We obtained valid data of the 106 nights. Level 1 did not exist. The data on the 106 nights was visualized per night using the chart of Fig. 4. Then, the number of points was counted in each Zone. The counted numbers with the averaged values of estimated instantaneous sleep satisfaction levels per one night are shown in Table II.

As shown in Fig. 5, the ratio at which the number of points at Zone A was greater than those at Zone D is 82/82 when the average value of estimated instantaneous satisfaction during sleep was level 3 or more. Furthermore, the ratio at which the number of points at Zone C becomes larger than those at Zone B was as high as 13/24 when the average value of estimated instantaneous satisfaction during sleep was less than level 3.

| No. | Average † | Zone A (over 3) | Zone D (less than 3) | Zone B (over 3) | Zone C (less than 3) |
|-----|-----------|----------------|---------------------|----------------|---------------------|
| 1   | 2.72      | 621            | 748                 | 549            | * 671               |
| 2   | 2.91      | 676            | 508                 | * 679          | 416                 |
| 3   | 2.60      | 888            | 652                 | * 783          | 573                 |
| 4   | 3.26      | o 690          | 503                 | 637            | 454                 |
| 5   | 3.17      | o 915          | 587                 | 868            | 517                 |
| 6   | 3.52      | o 847          | 441                 | 912            | 303                 |
| 7   | 3.20      | o 648          | 338                 | 626            | 228                 |
| 8   | 2.75      | o 610          | 573                 | * 573          | 472                 |
| 9   | 2.81      | 880            | 573                 | * 846          | 498                 |
| 10  | 2.85      | 787            | 793                 | * 775          | 605                 |
| 11  | 2.62      | 616            | 569                 | * 638          | 443                 |
| 12  | 2.58      | 471            | 684                 | 460            | * 596               |
Table II. The result of counted number of points in novel scatter plot chart (continued).

| No. | Average † | HF Zone A (over 3) | LF/HF Zone D (less than 3) | Zone B (over 3) | LF/HF Zone C (less than 3) |
|-----|-----------|-------------------|--------------------------|----------------|--------------------------|
| 13  | 2.11      | 403               | 716                      | 339            | * 662                    |
| 14  | 2.36      | 441               | 440                      | 381            | * 427                    |
| 15  | 2.23      | 587               | 804                      | 546            | * 757                    |
| 16  | 2.74      | 597               | 600                      | 532            | * 559                    |
| 17  | 2.37      | 584               | 511                      | * 486          | 463                      |
| 18  | 2.87      | 854               | 604                      | * 789          | 523                      |
| 19  | 2.45      | 702               | 690                      | * 671          | 592                      |
| 20  | 3.53      | o 943             | 493                      | 963            | 320                      |
| 21  | 3.07      | o 507             | 347                      | 447            | 318                      |
| 22  | 3.69      | o 1154            | 391                      | 992            | 408                      |
| 23  | 3.56      | o 719             | 332                      | 613            | 327                      |
| 24  | 3.90      | o 860             | 285                      | 929            | 201                      |
| 25  | 3.21      | o 430             | 279                      | 395            | 282                      |
| 26  | 3.51      | o 995             | 500                      | 911            | 443                      |
| 27  | 2.56      | 492               | 623                      | 414            | * 561                    |
| 28  | 2.95      | 494               | 545                      | * 467          | 463                      |
| 29  | 3.42      | o 813             | 462                      | 792            | 388                      |
| 30  | 3.01      | o 569             | 406                      | 565            | 392                      |
| 31  | 3.78      | o 778             | 335                      | 752            | 208                      |
| 32  | 3.60      | o 853             | 414                      | 761            | 366                      |
| 33  | 3.37      | o 825             | 480                      | 803            | 466                      |
| 34  | 3.12      | o 569             | 370                      | 531            | 324                      |
| 35  | 3.82      | o 755             | 219                      | 720            | 141                      |
| 36  | 3.66      | o 1109            | 441                      | 1059           | 356                      |
| 37  | 3.01      | o 778             | 739                      | 751            | 611                      |
| 38  | 3.30      | o 652             | 382                      | 580            | 379                      |
| 39  | 3.33      | o 904             | 624                      | 780            | 524                      |
| 40  | 3.54      | o 731             | 408                      | 696            | 342                      |
| 41  | 3.08      | o 459             | 295                      | 455            | 215                      |
| 42  | 3.59      | o 696             | 393                      | 651            | 321                      |
| 43  | 3.59      | o 825             | 301                      | 700            | 287                      |
| 44  | 3.11      | o 522             | 350                      | 474            | 314                      |
| 45  | 3.52      | o 1066            | 435                      | 958            | 370                      |
| 46  | 3.38      | o 637             | 295                      | 539            | 305                      |
| 47  | 3.67      | o 1043            | 423                      | 999            | 320                      |
| 48  | 3.54      | o 912             | 351                      | 849            | 351                      |
| 49  | 3.80      | o 1150            | 235                      | 1041           | 208                      |
| 50  | 3.29      | o 711             | 286                      | 626            | 267                      |
| 51  | 3.94      | o 538             | 87                       | 477            | 96                       |
| 52  | 4.02      | o 1140            | 132                      | 1043           | 117                      |
| 53  | 4.04      | o 917             | 144                      | 859            | 119                      |
| 54  | 4.21      | o 709             | 91                       | 663            | 88                       |
| 55  | 3.98      | o 907             | 106                      | 872            | 97                       |
| 56  | 4.11      | o 1130            | 141                      | 1007           | 140                      |
| 57  | 4.26      | o 1271            | 100                      | 1200           | 91                       |
Table II. The result of counted number of points in novel scatter plot chart (continued).

| No. | Average † | Zone A (over 3) | Zone D (less than 3) | Zone B (over 3) | Zone C (less than 3) |
|-----|-----------|-----------------|---------------------|----------------|---------------------|
| 58  | 3.25      | 780             | 382                 | 730            | 362                 |
| 59  | 3.52      | 795             | 283                 | 750            | 242                 |
| 60  | 3.72      | 807             | 174                 | 743            | 181                 |
| 61  | 3.69      | 766             | 202                 | 679            | 176                 |
| 62  | 3.00      | 583             | 538                 | 526            | 497                 |
| 63  | 2.83      | 568             | 640                 | 481            | * 607               |
| 64  | 3.38      | 858             | 388                 | 838            | 320                 |
| 65  | 3.94      | 1082            | 161                 | 1037           | 138                 |
| 66  | 3.32      | 733             | 373                 | 702            | 356                 |
| 67  | 3.89      | 1051            | 158                 | 944            | 144                 |
| 68  | 3.94      | 780             | 132                 | 731            | 115                 |
| 69  | 3.77      | 816             | 189                 | 796            | 175                 |
| 70  | 2.89      | 592             | 619                 | 518            | * 563               |
| 71  | 3.40      | 628             | 198                 | 562            | 173                 |
| 72  | 3.42      | 871             | 323                 | 780            | 332                 |
| 73  | 3.59      | 815             | 250                 | 773            | 254                 |
| 74  | 3.45      | 576             | 178                 | 508            | 190                 |
| 75  | 3.01      | 913             | 537                 | 753            | 598                 |
| 76  | 3.45      | 767             | 289                 | 683            | 287                 |
| 77  | 3.43      | 694             | 275                 | 643            | 264                 |
| 78  | 2.37      | 350             | 1035                | 393            | * 1158              |
| 79  | 2.90      | 561             | 521                 | 518            | 437                 |
| 80  | 3.29      | 890             | 540                 | 851            | 461                 |
| 81  | 3.18      | 708             | 406                 | 610            | 390                 |
| 82  | 3.41      | 961             | 373                 | 871            | 349                 |
| 83  | 3.95      | 946             | 129                 | 916            | 144                 |
| 84  | 3.67      | 983             | 255                 | 963            | 245                 |
| 85  | 3.64      | 718             | 190                 | 658            | 175                 |
| 86  | 3.70      | 917             | 189                 | 835            | 188                 |
| 87  | 4.18      | 883             | 81                  | 802            | 82                  |
| 88  | 3.31      | 641             | 304                 | 554            | 311                 |
| 89  | 3.75      | 837             | 178                 | 758            | 182                 |
| 90  | 3.36      | 902             | 335                 | 778            | 344                 |
| 91  | 3.03      | 552             | 536                 | 497            | 470                 |
| 92  | 3.11      | 743             | 529                 | 684            | 462                 |
| 93  | 3.12      | 848             | 575                 | 755            | 543                 |
| 94  | 3.25      | 756             | 493                 | 755            | 468                 |
| 95  | 3.35      | 874             | 432                 | 806            | 469                 |
| 96  | 3.71      | 892             | 247                 | 812            | 280                 |
| 97  | 2.47      | 166             | 445                 | 159            | * 346               |
| 98  | 3.58      | 951             | 278                 | 824            | 273                 |
| 99  | 3.29      | 763             | 324                 | 707            | 320                 |
| 100 | 3.39      | 902             | 474                 | 875            | 462                 |
| 101 | 3.30      | 966             | 429                 | 898            | 417                 |
| 102 | 3.14      | 871             | 534                 | 721            | 575                 |
Table II. The result of counted number of points in novel scatter plot chart (continued).

| No. | Average † | Zone A (over 3) | Zone D (less than 3) | Zone B (over 3) | Zone C (less than 3) |
|-----|-----------|-----------------|----------------------|-----------------|---------------------|
| 103 | 2.55      | 417             | 714                  | 428             | * 648               |
| 104 | 3.31      | ○ 680           | 402                  | 643             | 360                 |
| 105 | 3.39      | ○ 809           | 326                  | 713             | 400                 |
| 106 | 2.44      | 285             | 568                  | 301             | * 565               |

† The average of estimated instantaneous sleep satisfaction per night
○ The larger of the number of points at Zone A and Zone D
* The larger of the number of points at Zone B and Zone C

Fig. 5. The ratio of the number of points to the average of the estimated instantaneous satisfaction during sleep.

As shown in Fig. 5, there were 11 cases where Zone B had a higher number of points than Zone C when the average value of estimated instantaneous sleep satisfaction was less than level 3. Because the temperature inside the bed during the early stage of sleep was low in the winter season, the instantaneous sleep satisfaction was low estimated and it affected the average value. These experiments were carried out for 4 seasons, 1 year in Japan. In the winter season from No. 1 to No. 19, since the temperature inside the bed was lower than 15°C during the early stage of sleep, the estimated instantaneous sleep satisfaction level using the estimation formula was considerably lower. As a result, the mean value of instantaneous sleep estimates was less than level 3. Figure 6 shows a comparison of estimated sleep satisfaction with bed temperature at the same time axis in the winter season and summer season, respectively. As shown in Fig. 6(a), it can be seen that the level of the estimated instantaneous sleep satisfaction was very low when the temperature inside the bed was lower than 15°C at the beginning of sleep in the winter season. Figure 6(b) shows little change of temperature inside the bed during all sleeping time of the summer season. Figure 7 shows the ratio of the number of points excluding the data on the 9 nights that have a low average of the estimated satisfaction by the low temperature inside the bed during the early sleep in the winter season as shown in Fig. 6(a). The ratio at which the number of points at Zone C was greater than those at Zone B is 13/15. Therefore, these were the results that support the hypothesis.

4. Conclusion
In this paper, we visualized and evaluated the relation between estimated instantaneous sleep satisfaction and ANS by means of the proposed novel scatter plot chart. The relation between sleep satisfaction and the ANS was found to be the expected relation. It was thought that the proposed method will be helpful in estimating sleep satisfaction and evaluating states of the ANS in real-time. We aim at a system that supports the next morning’s awakening more comfortable from environmental conditions such as air conditioning and lighting in the bedroom by estimating instantaneous sleep
Fig. 6. Comparison of estimated sleep satisfaction and temperature inside the bed.

(a) In the winter season

(b) In the summer season

Fig. 7. The ratio of the number of points excluding the data on the 9 nights that have a low average of the estimated satisfaction by the low temperature inside the bed.

Parasympathetic nervous system (HF)
The number of point at Zone A > D
Cases over level 3 at averages of estimated instantaneous sleep satisfaction per night

Sympathetic nervous system (LF/HF)
The number of point at Zone C > B
Cases less than level 3 at averages of estimated instantaneous sleep satisfaction per night

There were limitations in this study that did not take into account the various internal and external effects of sleep, for example, physical exercise, a health condition, the intake of caffeine, alcohol, and food, sleep condition of the previous night, weekly variation, etc. Furthermore, there was insufficient consideration of the effects of respiration on the PNA. Therefore, the limitations of this study will be considered in future works. In addition, we will increase the number of subjects for a statistical hypothesis test. In order to increase the accuracy of the estimation formula, the introduction of other estimation methods will be reviewed and verification of stability will be performed in various ways.

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