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The Mental Workload of a Ship's Navigator using Heart Rate Variability

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Abstract: A human navigator attempts to handle the ship for safe navigation by judging navigational information on own ship's condition, targets and current-wind effects. He/she has the responsibility of human lives and the economic values to judge. The human navigator maintains high mental workload during the navigational watch keeping. Therefore, we need to develop a support system to reduce the mental workload with human-system cooperation based on the navigator's *KANSEI*, and we must research an index to assess the mental workload for the first step, as the research on the *KANSEI* of ship's navigator is not yet available in the world, In addition we depend on the professional's experience for the assessment. The purpose of this paper is to find characteristics of the mental workload using heart rate variability. The experiment is carried out on six types of sea area on the west side of Japan. The subject is the chief officer of a training ship at Kobe University.

Keyword: Human navigator, Navigational watch keeping, Mental workload, R-R interval, *SNS* value

1. Introduction

A human navigator gets navigational information from ones own ship's conditions and its navigational environments through five senses. This has to be recognized and analyzed in order to safely navigate the vessel.

For modern navigation, the human navigator is supported by useful navigational instruments, such as RADAR (RAdio Detection And Ranging) with which he/she can get the target information (distance and direction), ECDIS (Electronic Chart Display Indication System) with which he/she can get the nautical chart information on the display, and GPS (Global Positioning System) with which he/she can get own ship's position and so on. He/she has obtained the convenience and human ability promotion from human-systems cooperation. Now, we mainly request the system to draw out the ability of human navigators. In other words, it puts a navigator's *KANSEI* to practical use, and its system naturally guides him/her to navigate safely. Here, *KANSEI* is an individual sense, and its ability is not always achieved through experience. We define *KANSEI* as a sense including perception, recognition and awareness at conscious and unconscious levels. It is said that there are public, artist and professional *KANSEI* types (see Inokuchi et al, 1994). The research on *KANSEI* is done for art, music and marketing and so on (see Gyoba and Hakoda, 2000; see Tsuji, 1997). However, the *KANSEI* of a ship's navigator is not thought in the world. Moreover, we must develop friendly navigational instruments to reduce a human navigator's mental workload, since the members of a ship's crew decrease in order to reduce the overheads of ship's company, and the human navigator takes on a heavy responsibility during navigational watch keeping.

The first step in our study is to find a proper index of system assessment. We propose an evaluation method of the navigator's mental workload using heart rate variability, which is used to evaluate the mental workload of air pilots and car drivers in transport systems and is a better indicator than other indices. Here, we think that the physiological response that is an inner response is a most important index for the assessment of navigational systems when supporting safe navigation, because with all the excellent instruments, the human navigator maintains safe navigation efficiently.

The experiment is carried out on the human navigator in six types of sea areas on the west side of Japan in order to find characteristics of the mental workload for different navigational environments, such as congested area, narrow area, open area and so on. The subject is the chief officer of the training ship of Kobe University, the "Fukae-maru".

The results show that the mental workload for ship handling differs from each sea area. To be exact, the mental workload increases while the judgement of the ship handling is required in congested sea areas with fishing boats and it is affected by the wind. The mental workload decreases in open sea. We know that our proposed index can evaluate a human navigator's mental workload and human-systems cooperation.

2. Measurement of R-R Interval

We measured the subject's heart rate variability in six types of sea area to find the characteristics of a human navigator's mental workload during navigational watch keeping. We selected the R-R interval from heart rate variability because the amplitude of R peak is remarkable in comparison with other waves, and we are able to easily detect the peak point. Moreover, the validity of the R-R interval is guaranteed by our research (see Murai et al, 2001; see Murai et al, 2003). The outline of the R-R interval and the related experiments are described below.

2.1 R-R Interval

A heartbeat consists of P, Q, R, S and T wave; the P wave is reflected by atrial depolarization; QRS waves are reflected by ventricular depolarization; the T wave is reflected by ventricular depolarization. An electrocardiogram is shown in Figure 1. From figure 1, the R-R interval is the peak point R to the next peak. Its interval is always variable for the physical and emotional conditions, and the characteristics will differ among navigational conditions.

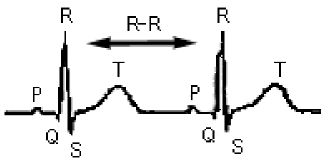

Fig.1. R-R interval

2.1 Experiment

The R-R interval in six types of sea area were measured. These areas are "*Kii Suido* (①)", "*Hyuga Nada* (②)", "*Akasi Kaikyo* (③)", "*Tosa Wan* offing (④)", "*Turusima Suido* to *Kurusima Kaikyo* (⑤)" and "*Sumoto Ko* offing (⑥)". Behavior was observed using the Work-Sampling method every second. The locations of each sea area are shown in Figure 2. Figure 2 shows the west side of Japan from "*Kyusyu*" to "*Osaka*". About types of sea area, the name of "*Suido*" means channel, the name of "*Kaikyo*" means strait, the name of "*Wan*" means bay, the name of "*Ko*" means harbor and the name of "*Nada*" means open sea (see Japan Navigation Glossary, 1993). The passage route which lots of vessels follow is usually set in the channel and strait; here the channel is larger than the strait (①,③,⑤). The harbor and bay are congested by lots of kinds of vessels which are leaving/entering port (⑥). However, we can keep to the open sea in "*Tosa Wan* offing" because it fronts on the Pacific Ocean and is not a domestic area (④). We can also keep to the open sea in "Hyuga Nada" where we see practically nothing except for some islands (②).

The duration of R-R measurement is from 0400 hrs to 0800 hrs (four hours navigational watch keeping) in "*Tosa Wan* offing", from 1600 hrs to 2000 hrs (four hours navigational watch keeping) in "*Kii Suido*" and "*Hyuga Nada*", from 0400 hrs to 0600 hrs (two hours navigational watch keeping) in "*Turusima Suido*" to "*Kurusima Kaikyo*", from 1600 hrs to 1800 hrs (two hours navigational watch keeping) in "*Akasi Kaikyo*" and from 0800 hrs to 1000 hrs (two hours navigational watch keeping) in "*Sumoto Ko* offing". The total number of hours for the experiment is eighteen hours. The R-R interval is measured with millisecond accuracy in the range of 200 to 4,090 milliseconds. Also, the heart rate monitor is Holder-type, with three electrodes placed on the skin.

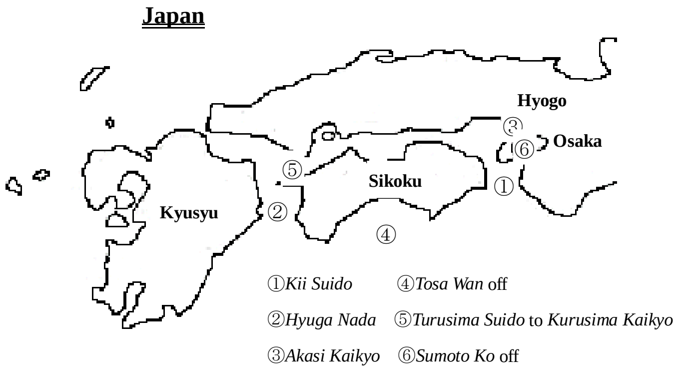

Fig.2. Experimental area to measure R-R interval during navigational watch keeping

Concerning the training ship, her length is 49.95 meters, breadth 10.00 meters and gross tonnage 449.00 tons. The appearance of the training ship and a scene of the navigational watch keeping in the wheelhouse are shown in Figure 3. The subject is the chief officer of the training ship "Fukae-maru" of Kobe University, Faculty of maritime sciences. The subject has twenty-nine years of experience on board and is forty-seven years old.

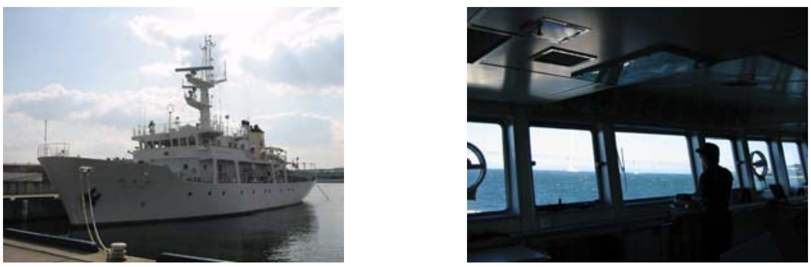

Fig.3. Training ship of Kobe University, the “Fukae-maru”, and a scene from the navigational watch keeping

The experimental conditions in the six types of sea area are shown in Table 1. From table 1, the ship was affected by strong winds in “*Akasi Kaikyo*” and “*Sumoto Ko* offing”. Careful consideration to the weather conditions are given in the results. Also, “bc” means “Blue sky and Cloudy” as it was fine weather.

Table 1. Experimental conditions in six types of sea area

Experimental Area	①*Kii Suido*	②*Hyuga Nada*	③*Akasi Kaikyo*	④*Tosa wan* offing	⑤*Turusima* to *Kurushima*	⑥*Sumoto Ko* offing
Ship’s speed [knot]	10.5	12.8	12.0	12.0	12.3	Var.
Ship’s course [deg]	182	027	065	228	055	Var.
Wind direction [deg]	SSW	South	SSE	West	SE	SSE
Wind velocity [knot]	12	19	30	14	2	25
Weather	bc	bc	bc	bc	bc	bc
Atmosphere [hPa]	1009.5	1010.3	1008.8	1009.8	1011.4	1009.7
Temperature [℃]	29.8	29.0	30.8	28.0	27.5	28.3
Water temp. [℃]	29.7	27.8	28.8	28.5	24.8	27.0

3. Analysis of R-R Data

We analyze the measured data in the time and frequency domain. The analysis, based on time domain, calculates the mean, standard deviation and the ratio of mean to standard deviation. The analysis, based on frequency domain, calculates Low Frequency (*LF*), High Frequency (*HF*) and Sympathetic Nervous System (*SNS*) value. We divide considerations between navigational watch keeping in the morning (0400 hrs to 0800 hrs) and evening (1600 hrs to 2000 hrs) because the characteristics are different due to the rhythm of a day. Here, area number ① to ③ is the navigational watch keeping during the morning period and ④ to ⑥ is the evening.

3.1 Analysis based on Time Domain

We calculate the heart rate (*HR* [bpm]) with the measured R-R interval using the following equation (1). After that, we calculate the mean (μ), standard deviation (*SD*) and the ratio (ρ) of mean to standard deviation using *HR*.

$$HR = \frac{1}{x_i / 1000} \times 60 \tag{1}$$

Here, x_i is the value of the R-R interval at measurement number i.

3.2 Analysis based on Frequency Domain

We analyze the frequency component (*LF* and *HF*) of the R-R interval which shows an activity of the sympathetic nervous system and the parasympathetic nervous system. We calculate *LF*, *HF* and *SNS* values (see Kobayashi and Senda, 1998; see Murai et al, 2001) using a Fast Fourier Transform (FFT) and Maximum Entropy Method (MEM) after interpolation with the Cubic-spline-function. Here, *LF* is the frequency component from 0.04 to 0.15 Hz, and *HF* is the frequency component from 0.15 to 0.40 Hz (see Ohtsuka, 1994). The FFT, MEM and *SNS* values are calculated using the equation (2), (4) and (5). We use FFT to find the characteristics of each sea area and MEM to find the characteristics of the events in each sea area.

We show the FFT in equation (2).

$$A_k = \sum_{j=0}^{N-1} a_j \times e^{-2\pi i/N} \tag{2}$$

Here, A_k is the amplitude of spectrum at frequency k, N is the total data number, a_j is the R-R data at data number j and i is an imaginary number. We use the FFT of Cooly-Tukey type (see Cooly and Turkey, 1965).

MEM estimates the spectrum by calculating the Auto-Regressive model. If the model shows in the equation (3), the spectrum of MEM is calculated by equation (4).

$$y(t) + \phi(1)y(t-1) + \ldots + \phi(p)y(t-p) + \sigma_w \varepsilon(t) = 0 \tag{3}$$

$$Y(k) = \frac{\sigma_w}{1 + \sum_{\tau=1}^{p} \phi(1) e^{-i2\pi k\tau / N}} \qquad (4)$$

Here, *Y(k)* is the amplitude of spectrum at *k*, *N* is the total of data number, τ is time lag, and *i* is an imaginary number. We calculate the spectrum every thirty seconds.

We calculate *SNS* values by using FFT or MEM in the equation (5).

$$SNS = \frac{LF}{HF} \qquad (5)$$

The *SNS* value is an effective index, which can evaluate the activity of both the sympathetic nervous system and the parasympathetic nervous system at the same time; its values increase while the human navigator keeps the mental workload.

4. Results

The results of the mental workload for each sea area are shown for μ , *SD*, ρ , *LF*, *HF* and *SNS*, and the relationship between the mental workload and the wind velocity is considered. We attach “A” as A.M. and “P” as P.M. to the number of each sea area (① to ⑥).

4.1 Mental Workload for Each Sea Area

We show the mental workload in six types of sea area using mean, standard deviation and *SNS* values in Figure 4. The *SNS* value is calculated by FFT. In figure 4, the bar shows the *SNS* value, the dot shows μ and the vertical line shows *SD*. The values of all parameters (μ , *SD*, ρ , *LF*, *HF* and *SNS*) are shown in Table 2. In Table 2, the numbers from (1) to (3) show the order of the value in the morning period and during the evening navigational watch keeping.

From the results, the mean of *HR* increases in “*Sumoto Ko* (⑥A)”, “*Kii Suido* (①P)”, “*Akasi Kaikyo* (③P)” and “*Tsurusima Suido* to *Kurusima Kaikyo* (⑤A)” where the subject needs make judgements to avoid fishing boats and control the engine. *SD* and mean have the same tendency. The *SNS* value increases in “*Sumoto Ko* (⑥A)”, “*Turusima Suido* to *Kurushima Kaikyo* (⑤A)” and “*Hyuga Nada* (②P)”. However, these values decrease in "*Tosa Wan* (④A)" where the open sea fronts on to the Pacific Ocean.

We know that the characteristics of *HR* differ from the *SNS* value, and the *SNS* value is better than *HR* by the subjective evaluation. We also evaluate this using two professionals. The frequency component of the R-R interval shows well the relationship between the subject's behavior when needing to judge the ship handling and the increase of *SNS* value. In other words, this result shows that it is difficult to distinguish between the physical workload and the mental workload using *HR*.

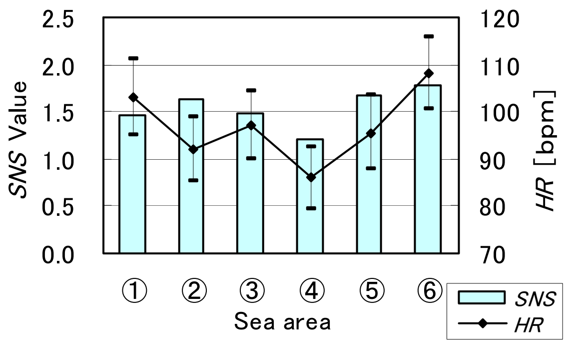

Fig.4. Mental workload in six types of sea area using the mean of *HR*, *SD* of *HR* and *SNS* values

Table 2. The values of μ , *SD*, ρ , *LF*, *HF* and *SNS*

	μ	*SD*	ρ	$LF\times10^6$	$HF\times10^6$	*SNS*
①A	103 (1)	8.1 (1)	0.078 (1)	19.8	13.6	1.46 (3)
②A	92 (3)	6.8 (3)	0.074 (2)	19.7	12.2	1.62 (1)
③A	97 (2)	7.2 (2)	0.074 (2)	7.0	4.7	1.48 (2)
④P	86 (3)	6.8 (3)	0.079 (2)	10.9	9.0	1.21 (3)
⑤P	96 (2)	8.0 (1)	0.083 (1)	21.0	12.5	1.68 (2)
⑥P	108 (1)	7.5 (2)	0.069 (3)	6.0	3.4	1.79 (1)

(①*Kii Suido*. ②*Hyuga Nada*. ③*Akashi Kaikyo*. ④*Tosa Wan*. ⑤*Turusima Suido* to *Kurushima Kaikyo*. ⑥*Sumoto Ko*.)

The characteristics of a human navigator's mental workload differ from sea area to sea area. We may be able to evaluate a human navigator's mental workload for various conditions on board. However, we do not know the events' characteristics for ship handling in each sea area, as only the average tendency is shown in figure 4 and table 2. Therefore, it is necessary to figure out the relationship to the events in each sea area.

4.2 Mental Workload for Events during Navigational Watch Keeping

The relationship between the mental workload and the behavior is shown using *SNS* values during navigational watch keeping in "*Akasi Kaikyo* (③)" and "*Turusima Suido* to *Kurushima Kaikyo*" in Figures 5 and 6. There are the passage route in"*Akasi Kaikyo*" and "*Kurushima Kaikyo*". Two passage routes are picked up from six types of sea area in order to discover the common characteristics of a human navigator's mental workload. We think that it is easy to estimate a subject's behavior for the passage routes because the ship's course is decided by following the local traffic rules. The *SNS* value is calculated by MEM.

"*Akasi kaikyo*" is narrow with a maximum current speed of 7 knots and a passage route 1,500 meters in width. "*Kurushima Kaikyo*" is also narrow with a maximum current speed of 10 knots and a passage route 1,200 meters in width. These areas are difficult to handle a ship in Japan. In figures 5 and 6, the spectrum is the ratio to the total of the spectrum, and the horizontal lines indicate mean values of *SNS* value.

Figure 5, numbers (I) to (IV) show the main events of the subject's behavior which are obtained by observation using the Event-Sampling method every second. From figure 5, the *SNS* value and its fluctuation increases at the entrance of the passage route (I, I'), the judgement of ship handling (II) and chart work (III). Moreover, it increases while the wind affects the ship (IV, IV').

The results show that *SNS* values increase while the human navigator needs to judge the ship's handling and feel the mental workload emotionally. The human navigator pays attention not only to the avoidance of targets but also to wind-current effects. The characteristics of the mental workload with the *SNS* value are shown by the 'level', 'response' and 'reaction' of the *SNS* value.

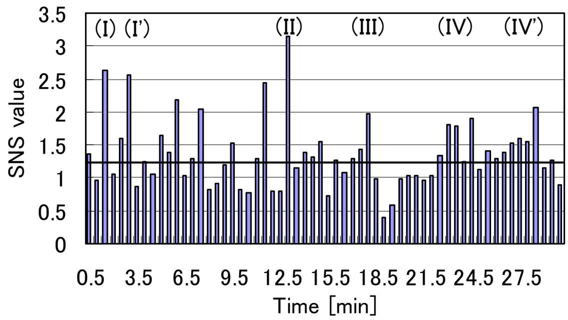

Fig.5. Mental workload with *SNS* values for events in “*Akasi Kaikyo*”

In figure 6, (a) to (h) show the main events of the subject’s behavior obtained by observation. From figure 6, the *SNS* value and its fluctuation increases during the communication with the Traffic Advisory Service Center (a), the captain comes to the wheelhouse (b), the ship handling to enter the passage route (c), the brain work required in answering our questionnaire (shown in parenthesis in the figure) (d), the judgement to avoid target ships ((e): fishing boats, (f): a container ship), taking over the navigational watch including chart work (g) and surprise/pleasure in finding dolphins (h).

These results support the characteristics in “*Akasi Kaikyo*” which are shown. The *SNS* values increase remarkably during the judgement of the ship handling in controlling the ship’s course, and the level of the *SNS* value is higher and the response is sharper. During the approach to the entrance to the passage route and feeling the mental workload emotionally, the level of the *SNS* value is higher and the response/reaction is longer.

From the figure, we may consider that the reaction time of the *SNS* value is proportional to the brain working time, and the duration depends on the kinds of judgement required for ship handling when keeping safe navigation.

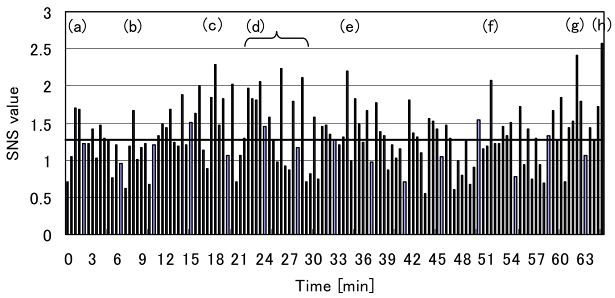

Fig.6. Mental workload with *SNS* values for events at "*Kurushima Kaikyo*"

We propose a method to express the level of the mental workload using the *SNS* value in order to find the relationship between the navigator's behavior and the characteristics of *SNS* values. This is calculated by the ratio of the peak to mean in Tables 3 and 4.

Table 3. The relationship between the ratio of the peak to mean of *SNS* values and the events of the subject's behavior in "*Akasi Kaikyo*"

Event	Time [min]	Peak / Mean
I	0.5	1.96
I'	1.0	1.90
II	0.5	2.33
III	1.5	1.47
IV	2.5	1.41
IV'	3.5	1.53

Table 4. The relationship between the ratio of the peak to mean of *SNS* values and the events of the subject's behavior in "*Kurushima Kaikyo*"

Event	Time [min]	Peak / Mean
a	1.0	1.30
b	0.5	1.27
c	2.0	1.74
d	3.5	1.70
e	1.0	1.67
f	0.5	1.57
g	2.0	1.83
h	1.5	1.95

From tables 3 and 4, we know the relationship between the human navigator's mental workload and the characteristics of the *SNS* value; 1) In the case of the human navigator making judgement to avoid target ships and approach the course line, the level of the *SNS* value is the highest and the response to the *SNS* value is the sharpest. Its events are shown at I, I’, II, c, e and f. 2) In the case of the current and/or wind affecting the ship, the response of the *SNS* value is not sharp and the reaction of the *SNS* value is longer. Its events are shown at IV and IV’. 3) In the case of the human navigator work, including making emotional decisions, the level of the *SNS* value is higher and the reaction longer. Its events are shown at III, d and g. 4) In the case of the human navigator doing general work, the level of the *SNS* value is lower and the reaction shorter. Its event is shown at A. 5) In the case of the human navigator appealing to emotions, the response of the *SNS* value is the sharpest. Its events are shown at b and h. We can confirm that the mental workload is distinguished by ‘level’, ‘response’ and ‘reaction’ to the *SNS* value.

4.3 The Relationship between Mental Workload and Wind Velocity

The human navigator pays attention not only to targets but also to wind and current from the results. The relationship between the mental workload and wind velocity is shown using *SNS* values in Figure 7. In figure 7, the values of wind velocity and *SNS* values are the mean of each sea area.

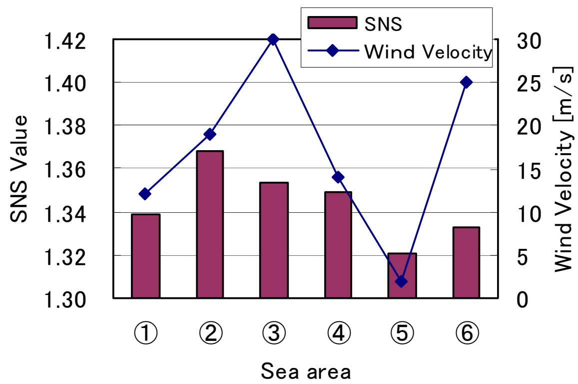

Fig.7. The relationship between the mental workload and wind velocity

From figure 7, the mental workload has the same tendency to decrease/increase in proportion to the wind velocity except for strong wind (③, ⑥). The human navigator is sensitive to wind conditions, and the *SNS* value shows the mental workload well. As for the results of strong wind (③, ⑥), we think that the mental workload is not so remarkable as it is clear for the human navigator.

5 Conclusions

We propose the quantitative index using the R-R interval in order to evaluate the relationship between a human navigator's mental workload and the navigational conditions. The experiment is carried out for a professional in six types of sea area in Japan.

From the results, the *SNS* value is better than the heart rate, and the frequency components of the R-R interval were effective in finding the characteristics of the mental workload for each navigational condition. We can distinguish among each characteristic of the mental workload by using the level, the response and the reaction to *SNS* values.

Our future aims are 1) to carry out the experiment on other professionals, 2) to analyze the frequency components of the R-R interval in detail, and 3) to find an absolute criterion for individual differences.

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