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A Basic Experimental Study on Mental Workload for Human Cognitive Work at Man-Machine Interface

By

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Osamu WAKAMORI** and Yoshinori NAGAI***

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Abstract

The nature and measurement methods of mental workload (MWL) for human cognitive activity at man-machine interface (MMI) were firstly discussed from the viewpoint of human information process model. Then, a model VDT experiment which simplifies the actual human-computer-interaction situation at MMI, was conducted for several subjects, where two subjects participated in experiment series and tried to solve the same cognitive task in competition. Adopted experimental parameters were (i) different kinds of cognitive task, and (ii) cycle time of information display, to see the influence on MWL characteristics from psycho-physiological viewpoint. A special processing unit for eye camera was developed and used for measuring subjects' eye movement characteristics.

Concerning data analysis, total number of display presentation until problem solving (i.e., total information needed for problem solving) was assumed as anchoring objective measure for MWL, and the investigations were conducted from two aspects; (i) global interpretation on MWL characteristics seen in the subjects' behavior from viewpoint of human information process model, and (ii) applicability of MWL by means of biocybernetic method.

As regards to applicability of biocybernetic method, the nature of MWL characteristics was first divided into two aspects : (i) efficiency of visual information acquisition, and (ii) difficulty of inner cognitive process to solve problem, both in time pressure situation. Then, the data analysis results for eye movement characteristics were correlated to (i), while for heart rate characteristics, (ii).

1. Introduction

Recent progress in digital computer control and information technology has been promoting extensive automation in the process control systems of various plant engineering. But the resultant large-scale complexity of the process system has grown to exceed easy understanding of human operator who is in charge of safely operation of the machine system. So there arises a prevailing concern, from the aspect of safety and reliability of the whole system, on possibility of serious hazards caused by human error. To overcome this new problem, research and development for advanced interface technologies such as intelligent interface¹⁾ are now flourishing and in progress in every field of engineering with the common keywords such as "human-centered automation", "harmony between human and machine", etc.

As regards to discussions on harmony between human and machine, there is an exotic word called

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"mental workload", for scaling workload of human cognitive works at man-machine interface. This sort of matter surrounding mental workload has been treated in different ways in different fields; "information process" and "attention" in the field of experimental psychology, "time required to perform the task" in system engineering, "stress" in physio-psychology. And the importance of concept of mental workload is commonly recognized as an effective measure for interface adaptability to human, but the definition itself has been made in different manner on the basis of different background of researchers so that there has been no common definition for this vague word.

Reflecting the above trends, Kantowitz suggested to compose a comprehensive model of mental workload which stems from a model of human information processing²¹, by saying like this; "The ultimate objective of measuring mental workload is to give a number which shows or predicts how much mental work is given to the imposed task, but there are so many complex factors surrounding mental workload that it is impossible to sum up as a number. However, an important factor is the mental load for human to process the information on fulfilling the imposed task." He also reviewed the researches thus far conducted for measuring mental workload, and classified them into three categories: (i)subjective rating method, (ii)sub task method, and (iii)biocybernetic method.²¹ He argued that the subjective rating lacks objectivity and in the case of the sub task method, it sometimes has the difficulty of selecting proper sub tasks. On the other hand, he rated that the biocybernetic method such as the use of heart rate, electrodermal reaction, brain wave, and pupil size, would be promising one since it utilizes human unconscious reaction of physiology, but its proof of effectiveness depends upon the future research efforts. If we may state conclusively, it is necessary for the practical use of any mental workload measurement including biocybernetic method, to solve those problems such as (i)it can measure personal differences, (ii)it can compare the mental workloads for different task, (iii)it can measure the time change, and (iv)it brings no additional load to person.

Originally, human cognitive activity is internal activity, has personal difference, and has variability even for the same person, and so it is in fact very difficult for full understanding. Reflecting those specificity, the authors have been conducting basic laboratory experiments which simplifies the real working conditions to more idealized situation, in order to observe the fundamental characteristics of on-line, event-driven human problem solving behavior at man-machine interface.³¹ In their experiments, the number of the subjects for observation is rather limited to small number but they collect as many subject protocols as possible, such as verbal reports which are traditional means for experimental psychology, and many kinds of biocybernetic measures which are widely applied in the field of psycho-physiology.

In this paper, the authors will first discuss how they correlate their experiment method to mental workload measurement with general theories on human cognitive model from the standpoint of model of human information processing. Then they will proceed to the detailed descriptions on their conductance of a new basic laboratory experiment and the related data analysis procedures for obtaining anchoring objective measure for mental workload. They will then describe the detail of eye camera data processing system which they have developed by themselves for the data analysis of eye movement characteristics. Various biocybernetics measures obtained by the usage of eye camera and polygraph were data-processed, and the analyzed results will be discussed from the viewpoint of model of human cognitive information processing, and then they will proceed to discuss on the meanings of characteristics of eye movement and heart rate, from the two aspects of (i)efficiency of visual information acquisition, and (ii)difficulty of inner cognitive process to solve problem, both in time pressure situation.

2. General Discussion on Mental Workload and Experimental Method on Human Cognitives

2.1 Discussion on Mental Workload from Human Information Process Model

2.1.1. Microscopic Model on Human Information Processing and Mental Workload

Card, et al., constituted a model of human information processor which compares human cognitive functions to modern computer by assembling knowledges and findings of experimental cognitive psychology.⁴⁾ This is made by classifying human cognitive information process into three sub-systems of (i) perception system, (ii) cognitive system, and (iii) motor system. The individual systems have their own memories and processors, and their functions are specified by four parameter values (μ , δ , κ , τ). The memory contains information and it is specified by three parameters: capacity μ , duration time δ , and code type of information κ (physical, visual, acoustic and semantic). On the part of processors, they are characterized by cycle time τ which corresponds to the cycle time of various information processing in the respective processors. The parameter values of the three systems are listed in Table 1.

As for the cognitive system, it performs complex processing such as association, recognition, inference, etc., by the cognitive processor using two types of memory, short-term memory (STM) and long-term memory (LTM). The capacity of STM is restricted to 7 ± 2 chunks, and unless the information in STM are attended or refreshed incessantly, they will tend to decay within several seconds. The word "chunk" is the unit by which a set of information will lump together, and it is a very convenient idea for describing the nature of human memory that multiple information will tend to be compressed to less information than the apparent quantity by a proper organization of information structure. The cognitive system works as the repetition of the basically identical cycle that the information content of STM will activate a certain part of LTM of enormous memory quantity and then the STM content will be altered. The normal period of this process is around 70 msec in average with the time span between 25 and 170 msec, and if the task requirement or information quantity increases, the period will increase, while it can be decreased by accumulation of practice or familiarization.

As far as mental workload is concerned, Kantowitz proposed what is called "hybrid model"²⁾ where a kind of STM memory limitation by the model of human information processor is defined as "limited capacity", and the ratio of task requirement to the limited capacity is assigned as mental workload when we conduct a hybrid-type cognitive process mixed with parallel and serial processing. The notion of the proposed model is illustrated as shown in Fig.1. As shown in Fig.1, there are two types of mental process, one with attention, while the other, sub-conscious process. According to the model, the shortening of cycle time by familiarization is ascribed to the gradual transformation of attentional serial process to the sub-conscious parallel processing. Conclusively, the above stated model of mental workload is a microscopic aspect of mental workload which can take into account of chronological change of human cognitive nature even in micro scale of time.

2.1.2. Macroscopic Model on Human Information Processing and Framework of Protocol Analysis for Cognitive Experiment

From the more macroscopic viewpoint than by the previous section, the nature of human cognitive activity at man-machine interface is naturally thought as meaningful composition of elementary actions by the integration of the above mentioned microscopic information processing. As such models of human cognitive behavior where problem solving is made by the presented information through interface, there have been proposed various qualitative models, for example, Rasmussen⁵⁾, which commonly describe the problem in concern as the cycle of specific information process steps like observation of presented information, identification, interpretation, evaluation, planning of action, and then trigger of responsive actions.

In the course of such integrated cognitive activity phase, the major factors which influence the mental workload is thought to be the inadaptability of human cognitives, or in other words, mismatch of task

requirement to the two factors in human cognitives; (i) internal image for the given cognitive task (mental model), (ii) operational limitation of whole human information process.

Based on the model of cognitive behavior mentioned above, the authors depicted a model of internal cognitive activity with data factor for experimental analysis. The model is illustrated in Fig.2. According to the model, the scheme of internal world of cognitive information process is summarized as the state transition between the three stages of (i) observation/identification, (ii) interpretation, and (iii) evaluation/planning, with the bi-directional transition among the three stages. As far as data factors are concerned, they are the data more or less observable from outside and they are classified into three features of action, memory and emotion. In the subsequent part, we will explain the significance of multiple collection of subject protocols employed in our experimental approach by collating with data factors in Fig.2.

- (1) Action --- The records of action are the three data : (i) Automated log of interactive operation to interface, (ii) Eye movement data and (iii) Utterance of speech. There are two verbal reports, one is "Think-aloud protocol" during the execution of cognitive task, and the other, "Retrospective report" just after the task execution to verbalize problem solving strategy used by subject and the impression on task difficulty. Eye movement can be traced by eye camera and will be used for estimating visual information search behavior during task execution.
- (2) Memory --- Memory content is the matter which subject holds in mind and it is impossible for direct observation, therefore no ways other than to estimate through his utterance. According to Ericsson and Simon, however, think-aloud protocol is said to reflect subject's focus of conscious attention during task execution, and one can estimate the transition of STM contents through the think-aloud protocol.⁶¹ On the other hand, the retrospective report is rich in the generalized information for understanding subject's problem solving strategy and impression on problem difficulty.
- (3) Emotion --- Subject's emotional drive during problem solving can be estimated by verbal protocol, but biocybernetic information such as sudden changes of pupil size, heart rate, skin potential response, can be utilized for estimating it even if no verbal utterance is available in the experiment.

2.2 Definitions of Anchoring Measure of Mental Workload and Experimental Parameters for Present Experimental Study

In the present study, the authors assumed that the cognitive behavior of process operators who would perform process monitoring and control through man-machine interface as "data-driven, realtime, online problem solving activity" which will be stated as "understand and judge state transition rules of process based on the information sequentially presented on VDT interface". Then they conducted a model laboratory experiment which very much simplified the real situation, although the situation is the same type as "data-driven, realtime, online problem solving activity".

As already stated in the previous section 2.2.1, the mental workload (hereafter it is abbreviated as "MWL") has temporal variations microscopically during the course of problem solving. But in the present study, it is assumed that the MWL is the integration of this change for the whole time span between the start of cognitive task until problem solving. The resultant MWL is assumed to be given by the ratio of A/B , where A is total presented information quantity required for the subject to solve the imposed task, and B is the minimum information quantity originally sufficient for solving the problem by ideal solving strategy. Since B becomes constant if the cognitive task is clearly defined, therefore A becomes the experimental index which reflects the actual level of MWL (A/B) in this case. According to this experimental index of MWL, the ratio A/B is always larger than 1 and if A is as low as possible, it is interpreted as low MWL.

Therefore, in the present study, the information quantity A is taken as the objective measure of MWL to analyze the experimental results. Therefore, the anchoring measure of MWL experimental analysis is taken as A, that is, "total time series information presented on VDT until subject required to solve the cognitive task", and there are two experimental parameters to influence subject's problem solving process. They are (i) cycle time of presenting information on VDT and (ii) different nature of cognitive tasks imposed to the subject.

And to pursue common tendencies of cognitive behavior in the specificities of personal difference and temporal variability of the same person, we conducted experiments for three subjects with two times of the same tasks in different days for each subject. Concerning the relation of biocybernetic measures with MWL, we especially noticed various characteristics of eye movement and heart rate, and the data analysis were conducted to investigate whether or not any relationships between their characteristics and the anchoring measure of MWL.

3. Basic Laboratory Experiment

3.1 Overview of Experimental Program

3.1.1. Material for Cognitive Task Experiment

The material used for cognitive tasks is a state transition model of three-input, three-state as shown in Fig.3. In this case, three figures of $\bigcirc$, $\triangle$ and $\square$ in Fig.3 are "states", while the key numbers 1, 2 and 3 and the arrows attached to them are "input keys" which bring changes of figure according to the direction of arrows. Using this state transition model, three different kinds of cognitive task are given to the subject who will solve the problem automatically displayed on VDT screen by personal computer. There are two types of cognitive task, namely (i) "learning problem" to realize the rule of this state transition model, and (ii) "selection problem" to distinguish a right one from a set of given alternatives.

3.1.2. Protocols from Subject

For the experiment, the subject were asked to wear eye camera and to attach many electrodes for polygraph to measure various kind of biocybernetic signals. Those biocybernetic signals were automatically recorded by computer. The data on the problems given automatically to subject by computer, and subject's responses from touch panel and keyboard were also automatically recorded as operation records. Concerning verbal report, two kinds of verbal protocol were collected from the subjects, think-aloud protocol during the execution of each cognitive task, and retrospective report after the experiment.

3.1.3. Major Features in Experimental Program

The major features are summarized below concerning experimental conditions and procedure:

- (1) Experiment setting to the subject is "competitive experiment", where two subjects participated in each experimental series and tried to solve the same cognitive task competitively. This is to assure their efforts and attitude to solve the problem more seriously, and to bring about stressful situation more naturally.
- (2) Nature of problem solving by subject is "passive monitoring", that means, he/she was asked to solve problem by observing sequential changes of state transition automatically displayed on VDT by constant cycle time.
- (3) The sequence of automatic change was designed beforehand so that all the transition rules are given until a certain turns with as equal occurrence chances of all probable state transitions as possible, and then repeat the sequence after that turn. The reason for adopting this sort of regular sequential change is that

the problem difficulty to the subject can reflect on the observable number of display presentations until subject's problem solving.

- (4) The cycle time for automatic key change was set to three group : 3 seconds, 2 seconds and 1 second. The experiments were conducted with the slowest cycle time ones given in the first phase to familiarize the subject to the problem and then the cycle time was accelerated step by step.
- (5) Retrospective report were collected from subject by using the same formatted report sheet in which major question items were selected beforehand in order to compare easily the differences of problem solving strategy and impression of problem difficulty among different subjects.
- (6) Each subject took the same experiment two times by changing days and the partner for competitive experiment. This aims at eliminating or mitigating the influences of more or less inevitable factors such as physiological change, experience, etc., and to reduce common tendencies or characteristics caused by the preset experimental parameters.

3.2 Experimental Methods and System Setup

3.2.1. Description of Cognitive Tasks imposed to Subjects

There are three experiment series in the present experiment, the type of cognitive tasks for both experiment series B2 and B3 is "selection problem", while for B4, "learning problem". There are multiple numbers of test for those three experimental series, and for each series, two subjects start at the same time, solve the problems of each test in turn, and the series ends when the both finish all tests. The example of the VDT display is shown in Fig. 4 for experiment B2. In Fig.4, when either one of key number 1, 2 and 3 at the "Automatic changing part" is selected by red color change (like black part of key 1 in Fig.4), the figure in the upper part changes according to state transition model (no color change in case of the model shown in Fig.3). Also as shown in Fig.4, the progress of the test numbers and the score of right answer for both subjects are always displayed on the screen at the both sides of the figure change in the center, and beep sound and change of display background color tells the subject when the competitor finishes all tests in that experiment series. The contents of each experiment series are described in the followings;

(1) Experiment series B2 (Selection problem)

As seen in Fig. 4 of the display style for this experiment, there are three figures (Samples 1, 2 and 3 of different state transition model) in the lower part, and the subjects were asked to judge which is the right model by watching the cyclic changes of input key selection and the shape of figure in the center. In those sample figures below, there are no indications for input key numbers, and the directions of arrows are different with each other. The number of the tests are 33 in total with the cycle time of 3 seconds for the first 11 tests, then 2 seconds for the next 11 tests followed by 1 second for the last 11 tests.

(2) Experiment series B3 (Selection problem)

This experiment series is the same type as B2, except for the style of the sample figures below. The replaced sample figures are shown in Fig. 5. As seen in this figure, the difference of input key numbers is indicated by three letters E, P and L. Those E, P and L correspond to the input key numbers 1, 2 and 3, but the correspondance is different in each test. Concerning the arrow directions, they are identical allocation in this case.

(3) Experiment series B4 (Learning problem)

In this case, there are no sample figures in the lower part of VDT display, and the subjects were asked to observe the automatic changes of the input key selection with the subsequent shape change in the center and push the key on the screen when he/she understand the rule of state transition. After that, he/she was asked to write down the state transition model as he/she understand. Then, the right answer appears on the

screen, and he/she was asked to judge whether or not his/her answer was right. Since this experiment took more time for the subjects than B2 and B3, therefore, the total number of the tests is limited to 15, with 5 tests for each cycle time.

3.2.2. Prior Examination for Apparent Information Quantities to Problem Solving

We will consider how much cognitive information quantity will be needed for those three experiments. In case of B4, since the rule of the state transition model is to know three times "original shape of figure, input key number, changed shape", therefore if we think simply, the required total quantity is $3 \times 3 \times 3 = 27$ so that it exceeds by far the human limitation of STM capacity (7 ± 2 chunks). Therefore for the subject, the point of how to solve this is how to compress such large information quantity within his/her STM limitation.

In the cases of B2 and B3, if you judge which of the three samples is right after you completely understand the state transition by the same way as in B4, the needed information quantity would be as the same as or more than that for B4. But if you manage it by step-by-step elimination for wrong samples by monitoring automatic changes on VDT, then you will not need so many load as in B4.

There is a principle "rational behavior" among the different principles of human cognitive behavior, stating like "Human behavior is goal-oriented, and that is more rationally determined by the problem structure, available information, and human knowledge with processing capability." It is very interesting to know how the problem solving strategies which are brought by such human rational behavior would give rise to the difference in MWL among different subjects.

3.2.3. Configuration of Experimental System Setup

The configuration of the system setup for the present experimental study is depicted as shown in Fig. 6. In this competitive experiment, online data recording was needed simultaneously from the two subjects, and because of the limitation of experimental equipments available at hand, the system setup for biocybernetic measurement was different with each other between the side A and side B. The detailed system setup for side A is explained in Table 2, while in Table 3 for side B.

3.2.4. Record of Conducted Experiment with Subjects

The summary of the progression of conducted experiment is described in Fig. 7. Total subjects participated in the experiment were 5 students (P, Q, R, M, D), and the subject data used for experimental analysis are those for P, Q and R (P and Q were male student while R, female. P, Q, R were students in psychology course, while M, D were experimentors.) Each subject seated at the side A for the first time, while side B in the second time. In Fig. 7, the results of competition between subject pairs are also recorded. The winners who finished the game faster are indicated by ○ mark with the rate of right answers. As for the losers indicated by ●, the records of his/her performance at the time when the winner finished the game are also shown for the stage of test number and the rates of right answers until then and after that, other than the whole right answer rate after finishing all the tests. The maximum time per one test for problem solving were ca. 1 minute for B2, ca. 3 minutes for B3 while ca. 6 minutes for B4.

3.2.5 Data Processing as Timeline Chart

The data recorded from the both subjects were automatic log of operation records, eye camera data and polygraph data, and they were processed on work station to get a "timeline chart" as shown in Fig. 8. Timeline chart is a chronological diagram of various kinds of data records plotted with the same time scale in one sheet of paper, and in the case of competitive experiment, there are two different timeline charts for

two subjects at the both sides of A and B. The timeline chart shown in Fig. 8 is for subject P, test No. 16 in B3. This timeline chart is very useful to analyze the subject's physiological measures with correlating with each other and interpret subjects' mental process from the responses of various physiological measures. A typical interpretation will be described in the subsequent section 4.5 by using Fig. 8.

3.3 Eye Camera Data Processing System

3.3.1 General Functions of Eye Camera Data Processing System

The eye camera looks like a goggle as shown in Fig. 9, and the subject was asked to wear it on his/her head during the experiment. The whole device consists of two infrared cameras attached on both sides of his/her face, a small ITV camera on his forehead to take the subject's front view, two infrared LEDs which illuminate his/her both eyes, and two half mirrors in front of each eye. The principle of eye camera is illustrated as shown in Fig. 10.

As seen in Fig. 10, the camera of right-hand side is used to take a pupil image by infrared LED light which is reflected on eye surface and then guided by way of half mirror and mirror. Since we applied infrared light for both LED and camera, the subject is not dazzled by the light during the experiment. In addition, infrared light is well reflected on the subject's iris, so that in the picture taken by the camera, the part of pupil is very clear as a dark image as shown in Photo 1.

On the other hand of right eye, the camera of left-hand side is used for measuring the subject's eye point. It can identify the rotation angle of the eyeball by taking the LED image reflected on the cornea through the half mirror. As shown in Fig. 11, since the center of the eyeball is different from the center of the crystalline lens, the reflected LED image moves in the camera eye as eyeball rotates by the movement of eye point. The eye point thus identified by the reflected image is indicated as '+' mark, which is superimposed on the subject's front view image taken by the ITV camera (See Photo 2).

By this way, the eye camera can obtain the subject's front view image, the position of his/her eye point and the pupil image. We developed a special realtime image processing unit for the eye camera mentioned above as an extended board of a 16 bit personal computer, in order to compute the pupil area from the pupil image. The method of computation is as follows; Since the pupil is taken as a dark part on the image as seen in Photo 1, the original picture is converted to binary image by the threshold light intensity. The area of pupil is obtained by calculating the dark part in the binary image. In the processing unit, the whole image is divided into 350x262 small square pixels and counts the black ones, for measuring pupil area.

Because the eye camera uses a point light source for illumination, so the edge parts of the image becomes inevitably low light intensity. Therefore, a window frame which can be regulated manually on the image is introduced into the developed system. By using it, we can restrict the computing part for obtaining the right pupil area by cutting spurious dark parts in the edge. The method of setting the frame window is illustrated as seen in Photo 3. As seen in the photo, there are three vertical lines, and the center line is initially adjusted to the center of the pupil as the subject looks straight ahead. The window is divided into two parts by the three lines, and the both areas, i.e., right and left sides of the center line, can be also computed separately. By using this function, we can obtain not only the pupil area but also the horizontal eye movement.

Both the computed output data of pupil area and the horizontal movement of the eye position are displayed on VDT as time-varying graphs during the experiment. Photo 4 shows those time-varying graphs as superimposed on the picture of the subject's front view taken by ITV camera. In the analysis after the experiment, we will use only the time-varying data of pupil area mainly for the analysis of subject's eye blinking characteristics. For the analysis of eye focal point and saccade, we will use the eye mark data taken by the left-hand infrared camera.

The sampling time of the developed processing unit was designed as 60 times a second, so that the unit should be tightly connected to the personal computer for data acquisition. Therefore, it is designed as an I/O device directly connected to the bus line of the personal computer. Photo 5 shows the picture of the developed unit as the extended board of the personal computer.

3.3.2 Design of Realtime Image Processing Unit

Figure 12 shows the block diagram of the realtime image processing unit. The pupil image, which is taken by the right-hand infrared camera of the goggle, is fed to this unit as a NTSC video signal. The unit separates the horizontal and vertical synchronization signals from the video signal, and converts the intensity of the original signals to binary one by a fixed threshold level.

The horizontal and vertical synchronization signals are used to judge whether or not the image signal is within the frame window. The position setting of the window can be made by the data acquisition computer. The binary pixels are counted only when the pixel is within the window. Then, the count is held by the vertical synchronization signal, and is transferred to the data acquisition computer after the vertical synchronization timing.

The binary intensity signal is combined with the window frame position, the horizontal and vertical synchronization signals, and thus formed composite signals as NTSC video signal are output signals from the unit. The composite signals are used for monitoring the status of binary image and window frame position. The specific points on designing the image processing unit are described separately in the following paragraphs.

(1) Base clock

Since the developed unit measures pupil area by counting small pixels which are obtained by dividing the pupil image, the shape of the divided pixels should be square. The NTSC video composite signal has 262.5 horizontal scanning lines. On designing the unit, we assumed that one scanning line is equal to the height of the pixel. On the other hand, a scanning line was divided into 350 in horizontal direction so that a pixel becomes square shape. Since the scanning time of the video signal is $52.7 \mu s$ per one line, the base clock frequency becomes 6.6MHz by dividing it into 350 ($350:262.5 \approx 4:3$ is aspect ratio of VDT screen).

(2) Binary conversion

As mentioned above, since the video signal has a high frequency band more than 6MHz, it is necessary for binary conversion to apply a comparator which has a high frequency characteristics. We applied a high speed comparator, LM319, of which frequency limit is more than 10MHz, and has an open collector output to make the interface easy to digital circuit. The threshold level is set by a potentiometer since it is not necessary to change the level so frequently.

(3) Window frame

For setting the window frame on the original picture, five parameters (upper end, lower end, left end, center and right end) should be set to the computer, and this is manually made by monitoring the corresponding five lines on VDT to adjust them at proper positions. The processing unit can then count the black pixels within the window frame, and send the counted data to the data acquisition computer.

(4) Monitoring output

In order to check the appropriateness of the binary conversion and positioning of window frame, the

NTSC composite video signals can be monitored on VDT by the processing unit. The output monitoring image is the monochrome binary image, and the color of all the lines of the window frame is the opposite color of the background color of VDT.

4. Data Analysis

4.1 Interpretation of MWL Characteristics

4.1.1. Records of Performance for Individual Subjects with Their Retrospective Report

The operation records of all the subjects P, Q and R, on the time interval of display presentation (or cycle time of display presentation) and right answer rate, were first summarized for experiments B2, B3 and B4, with respect to the dependencies of (i) total numbers of display presentation until problem solving and (ii) right answer rate. As shown in Fig. 13, the results are grouped into six graphs in total, two graphs for each subject one for the first time and the other for the second time of the three experiment series. The way how to see each graph is like this; the horizontal coordinate denotes display numbers per second (ie., 1/cycle time), the left side of the vertical coordinate is number of display presentation until problem solving (cycle numbers), while the right side, rate of right answer in percentage (right score). Concerning the cycle number data for each experiment, average number is marked by X with the number span being indicated by straight line from the minimum to maximum numbers.

With respect to the retrospective reports taken from the three subjects, their answers were summarized as shown in Table 4, concerning subjective impressions on problem difficulty, their problem solving strategy, effect of speed change of display presentation and how they felt competition game with partner.

Concerning the overall performance order of the three subjects, the authors rated as $Q > R > P$, considering the both results mentioned above.

4.1.2. Reduction of Anchoring Measure of MWL

As seen in Fig. 13, the variations of total numbers of display presentation until problem solving against experimental parameters (differences in cycle time and nature of cognitive tasks) have the same trends for all subjects, notwithstanding the difference in experiment days: they increase with the acceleration of cycle time and for the difference of experiments, $B4 > B3 > B2$.

Since "total number of display presentation" is equivalent to "total information quantity needed until problem solving", this will be used as anchoring measure of MWL from the viewpoint of human cognitive information processing, and will be used for discussing various human cognitive characteristics, including the relations to the responses of various biocybernetic measures.

4.1.3. Interpretation of Common Tendencies seen in Subjects Behavior from the Viewpoint of Human Cognitive Information Processing

(1) Performance was degraded in every experiment as the display presentation speed becomes accelerated.

All the subjects reported: "When display speed becomes rapid (especially 1 second cycle time), I could not afford to manage memory and process it easily."

Interpretation: Increase of MWL by "time pressure" makes them difficult to fulfill the task.

(2) All the subjects used step-by-step elimination method for experiment B2 and B3. For B2, they noticed only the different parts in the arrow allocation among the three samples below, and drop out the wrong samples one by one, by watching automatic changes of input key selection followed by figure transition. But for B3, since the shape of the three samples are the same in arrow allocation, they first find suitable clues to decide which E, L, P correspond to 1, 2, 3 by comparing three samples below, and then apply thus

found clues to make step-by-step elimination for the three samples.

Interpretation: Preference of forming and applying a strategy for problem solving as light load as possible, by "principle of rational behavior".

- (3) Concerning concurrent "think-aloud verbalization", all subjects reported that they could not afford to speak what they were thinking during B2 and B3. (In reality, their utterance were very scarce in the both experiments.) But for B4, two subjects Q and R who managed to image state transition model well in their mind reported that they could memorize the rule better by speaking aloud.

Interpretation: Verbalizing task became the additional task requirement (sub-task) in both experiments B2 and B3, while not for B4. Since it well met the original task requirement for B4 so that it resulted in no additional load for those who used spatial memorization method very well.

4.1.4. Discussion on Subjective Ratings on Problem Difficulty

Except for subject P, the subjective difficulty order was not the same as the order of number of display presentations for the three experiment ($B4 > B3 > B2$). The subjects Q and R who used spatial memorizing method for B4 reported that B4 was rather easier than B3.

As already said in section 4.1.2, the number of display presentation is the necessary information quantity needed to solve the problem. In the cases of B2 and B3, if you use step-by-step elimination method, you can solve the problem rather earlier without understanding the rules of state transition model in concern. But in B4, you cannot solve the problem unless you collect all the rules and memorize them to report with confidence. Unlike subject P who hit upon the spatial memorizing method but could not manage it well, the easiness impressions by Q and R for B4 resulted from the fixation of spatial memorizing method as their workable mental model, although it took more time in B4 than in the other experiments.

The formation of human subjective impression whether or not he/her feels problem as easy one, depends on whether or not he/her could find any easy solution method and manipulate it easily, rather than the simple factor of how much time or information needed to solve the problem.

4.2 Eye Movement Data Characteristics

By using the eye camera and its data processing system mentioned in 3.3, data analyses were conducted on the eye camera data obtained from all the subjects who participated in competitive experiment in Side B. Since the eye camera used for side B can obtain the subject's eye point and pupil area, calculations of eye point velocity and time interval of eye blinking were easily made for later data analyses. The purpose of the data analyses was to investigate basic correlation between eye movement characteristics and human visual information search at MMI, from the following two points:

- (i) whether or not degree of saccade fraction would reflect the difference in the way of visual information search at MMI, and
- (ii) whether or not distribution function of eye blinking time interval reflect time margin of visual information acquisition from VDT.

(1) Relationship between Visual Information Search and Saccadic Eye Motion

The results of saccade fraction for all the subjects are shown in Fig.14, where the horizontal axis is cycle time of display, while the vertical axis is saccade fraction. The fraction of saccadic eye motion in this case is that eye point velocity is over 100 degree/second. It is commonly seen in Fig. 14, that the saccade fractions of all the subjects are high in B2, while low in B4. Since all subjects in B2 made frequent comparisons between automatic change of displayed figures in the center and three samples in the lower part of VDT

alternately, it is reasonable to have such high saccade fraction for B2. On the contrary, they only have to watch the central part in case of B4. However, for B3 which is similar to B2, the saccade fraction of subject R was low, although other subjects were the same high saccade fraction as in B2. The difference of subject R's visual information search between B2 and B3 will be mentioned afterwards. There seems no consistent tendency in saccade fraction change with acceleration of display cycle.

Next, the relation between visual information search behavior and experimental task were examined for subject R. The subject R's eye point data in both B2 and B3 are shown in Fig. 15, where the loci of eye point are expressed by the center of circle while period of eye fixation, by its radius. It is confirmed from Fig. 15 that although he looked at both the figure transition in center and samples below in both B2 and B3, the gaze period is short in B2, while it is long in the B3.

The calculations of eye velocity distribution functions for all test numbers are made for subject R, and the comparisons between B2 and B3 are as shown in Fig.16. In the both graphs of Fig.16, portion of velocity distribution more than 100 degree/second is summarized as the value at 100 degree/second. As seen in Fig. 16, the saccade fraction in B2 is higher than in B3 (see the part of velocity 100 degree/second), while portion of zero velocity is higher in B3 than that of B2(that means eye point tends to fix during B3).

The saccade fraction is higher in B2 since R always compared the rapid changes of displayed figure in center with three sample figures below by step-by-step elimination. On the contrary, the saccade fraction is lower and eye fixation is longer in B3, since R obliged to fix her eye point to identify which E, L, P correspond to 1, 2, 3.

Concerning B4, R watched automatic figure transitions just in central part, therefore, the saccade fraction naturally become low. Such interpretation is well consistent with the contents of retrospective report by subject R.

The reason why the saccade fraction of subject Q is not so low in spite of using the same strategy as that of R for B3, is that Q did not examine the difference of the arrows E, L and P so well as R, that Q often moved his eye point between figure transition and samples.

According to their retrospective reports, the subject Q felt that B3 was the most difficult one, while the subject R felt that B2 was more difficult than B3. Although their subjective impression may be influenced by the competition result that R beat Q in the game, the difference of their performance can be clearly seen in the difference of how to use their eyes.

(2) Relationship between Cycle Time of Display and Time Interval of Eye Blink

In retrospective report on whether or not all the subjects could catch up the acceleration of display cycle, they mentioned that they could not follow 1-second cycle. In this respect, the distribution functions of time interval of eye blinking were calculated for all the subject. The results are shown in Fig. 17 (a), (b) and (c) for subjects P, Q and R, respectively. In Fig. 17, the graphs of the obtained distribution functions are arranged as a matrix style, where experiments B2, B3 and B4 as rows, while cycle time of display presentation as columns. Furthermore, three broken lines are drawn at (cycle time + 0.5) seconds in every graph of Fig. 17, as to see whether or not most of eye blink interval is within the cycle time. The common tendencies observed among (a),(b) and (c) of Fig.17 can be summarized as follows;

- (i) The eye blink time interval distribution of 3-sec display cycle in experiment B4 is that of when the subjects have enough time to solve problems with fixing their eye points.
- (ii) On the contrary, the distribution of 1-sec display cycle in B2 is that of when they do not have enough time with moving their eye points.
- (iii) Generally speaking, almost all of the eye blink intervals are within the cycle time when display cycle is

slow. But when the cycle time becomes faster, the portion of eye blinks which are slower than display cycle time will tend to increase for most of subjects and experiments. This is interpreted as "skip of getting information from eye with display speed-up".

As a conclusion, if we assume that "Human executes cognitive information processing unconsciously with sequential sampling by eye blinks to the visual information coming continuously to retina through pupil", this suggests a hypothesis that "there is a correlation between the delay of internal information processing to the quick presentation of external information, and the increase of eye blink fraction in the part which is slower than cycle time of presentation".

4.3 Interpretation of Eye Movement Characteristics

Based on (i) the biologically supported knowledge that "there is no perception by visual system during saccade movement" and (ii) afore-mentioned hypothesis that "There is a correlation between omission rate of presented information and eye blink proportion in the part which is slower than information presentation cycle", effective information input rate denoted as FM (a measure related with efficiency of visual information acquisition) was estimated by using the eye movement characteristic data presented in the previous section. The FM was calculated by the following equation

$$F M = F \times (1 - S f)$$

where

$S f$ = saccade fraction, and

F = proportion of eye blink time interval distribution which is slower than (presentation cycle+0.5).

Figure 18 shows the calculated dependence of F and FM on presentation rate for all subjects P, Q and R, for all experiments B2, B3 and B4. As seen in all graphs in Fig.18, there is a general tendency that the FM tends to decrease as the display cycle becomes faster. This is in good agreement with the trend in Fig.13 that the number of presentations until problem solving increases as the display cycle becomes faster, and further it well corresponds with the subjects' impression that "it is hard to watch when 1-second display cycle", or "it becomes hard to watch as the cycle becomes faster". However, there is no significant difference in the FM as to the difference in cognitive task.

If we compare FM for the three subjects, the FM of Q is better than those of others, and moreover his FM is not degraded as the display cycle becomes faster. This seems to indicate the reason of his better performance than the others, already at the input stage of visual information acquisition.

4.4 Heart Rate Characteristics

Heart rate (or RR interval of ECG) is said to be governed by the opposing regulations between sympathetic and parasympathetic nerve systems, and it is a well admitted fact that heart rate is influenced by cognitive activity. In view of this, data analyses were conducted on average heart rate (m) and the standard deviation (σ) during the time span of experiments B2, B3 and B4. The results are given in Fig.19, where the two graphs for each subject show the variation of m and σ as function of display cycle. Also in Fig.19, the terms of M and Σ in the tables above the two graphs mean the average values of m and σ , over the whole time span of each experiment, and the obtained values of M , Σ and Σ/M are tabulated in the tables for each subject and experiment. We can see from this table, that the value orders of Σ and Σ/M for every

subject are in good agreement with that of number of display presentation (anchoring measure of MWL), that is, $B4 > B3 > B2$, although the difference between B3 and B2 are very minor in value. Concerning display cycle effect to heart rate, there are no consistent and common trends seen in Fig.19, for m and σ versus display cycle relationship.

As a conclusion of the results mentioned above, we may reduce a hypothesis that Σ and Σ/M would be a usable measure to distinguish MWL levels brought about by different nature of cognitive task, although premature at this phase of study.

4.5 Relation between Polygraph Data and Mental Stress

If we consider stress effect in this competitive experiment, we may point out two different factors; one is by the difficulty of cognitive task itself, and the other is the stress imposed by competition to the partner. It is therefore very difficult to interpret and give any plausible meanings to the temporal variations of physiological signals observed in the experiment. But the stress effect caused by competition would be well revealed by the help of retrospective report, and then it can be applied to interpret polygraph data from the viewpoint of competition stress.

A typical example was seen in the present study, from the data by subject P, whose time changes of heart rate in B2, B3 and B4 are given in Fig. 20. In Fig. 20, the horizontal co-ordinate means the progression of test number in each experiment, while vertical co-ordinate gives his average heart rate (beat/min) in each test number. The said stress effect can be seen at the two points of A (Test No. 16, B3) and B (Test No. 27, B2).

The point A is at the time when subject P was a half way of B3 experiment, but the partner had already finished all the test. P was defeated so early that he was very shocked. That is why his heart rate rises up suddenly at A. In fact, he reported afterwards that he was so shocked to see partner won so early that he felt as if his head becomes white!

On the other hand of A, his heart rate dropped down suddenly at B. In this case, both P and his partner did a very heated match with almost equal progression until later phase of the game. But he felt disappointed after he lost the game almost at the end of the game. The loss of enthusiasm to commit the game might give rise to the sudden drop of heart rate.

Concerning such stress effect on the polygraph data other than average heart rate, you will see the responses of various physiological signals as already shown in Fig. 8 (This timeline chart corresponds to the part of A in Fig.20). As indicated in Fig.8, there are simultaneous changes of various physiological signals at the instant when the partner won the game. They are instantaneous rise of heart rate, double wave pulse of SPR, and sharp pulses seen in both EOG and EEG. The strong pulses simultaneously appeared in both EOG and EEG might be ascribed to strong eye blinking at the point of A. If we may say further, those abrupt, simultaneous and strong responses in many physiological signals might be useful to predict the occurrence of a strong emotional drive in human mental process.

5. Conclusion

In this paper, the nature and measurement methods of MWL for human cognitive activity at MMI were first made by literature surveys from the viewpoint of human information process model. Then, a model VDT experiment which simplifies the actual human-computer-interaction situation at MMI, was conducted for several subjects, where two subjects participated in each experimental series and tried to solve the same cognitive task competitively, that means each subject tried to solve the problem displayed in turn on VDT screen as fast as possible independently with each other. During the experiment, as many kinds

of subject protocols as possible were recorded, such as automatic log of subjects' interaction to VDT display, verbal reports and various kinds of bio-cybernetic measures taken by eyecamera and polygraph. Concerning the experimental parameters, (i) different kinds of cognitive task, and (ii) change of display cycle time were the two major parameters to see the influence of the both parameters on the human cognitive characteristics from psycho-physiological point of view. A special processing unit for eye camera was developed and used for measuring subjects' eye movement characteristics.

Concerning the data analysis, we assumed that the total number of VDT display cycles until subjects' problem solving (which is proportional to the total time consumed for problem solving) as the anchoring objective measure for cognitive MWL, and the investigations were conducted from the two points; (i) global interpretation on the related MWL characteristics seen in the subjects' behavior from the aspect of human information process model, and (ii) applicability of MWL measurement by means of biocybernetic measures such as ocular measures and heart rate.

As regards to the investigation whether or not the biocybernetic measures would be utilized for estimating cognitive MWL, we separated the nature of MWL into two stages of cognitive process: (i) stage of information input from human visual system, and (ii) stage of inner cognitive process after information input.

As the results of experimental data analysis, we reduced the following two hypotheses on the meaning of biocybernetic measures with respect to the possibility of estimating MWL objectively:

- (i) The effective information input fraction through ocular system can be estimated by using the saccade fraction and distribution function of time interval of eye blinking, and
- (ii) The difficulty of the cognitive task as inner cognitive process would be reflected on heart rate data, with the ratio of standard deviation to average values of heart rate as a plausible measure of MWL scaling.

As a conclusion from a rather simplified basic laboratory experiment conducted for measuring human cognitive characteristics at MMI, we found out the significance of usage of multiple biocybernetic measurement for online, realtime estimation of various cognitives-related MWL characteristics of human-computer interaction at man-machine interface, although the tested biocybernetics instruments should be further improved, to the practical application for real MMI problems.

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Fig. 1 Hybrid model of mental workload.

Conceptual Model of Human Cognitive Behavior

Fig.2 Conceptual model of human cognitive process and data factors.

Fig.3 Illustration of state transition model used for cognitive task experiment.

Fig.4 Example of VDT display for Experiment Series B2.

Experiment B3

Fig.5 Example of sample style for experiment Series B3.

Fig.6 Illustration of whole experimental system setup.

Subject		Experiment			Partner subject	Experiment date
		B2	B3	B4		
P	First time	● (85) 90 (89→100)	● (48) 72 (66→78)	● (56) 12 (0→25)	M	1989. 12.2
	Second time	○ 90	● (100) 84 (84→100)	○ 56	Q	1989. 12.5
Q	First time	● (70) 69 (77→55)	● (94) 72 (70→100)	● (69) 25 (20→33)	P	1989. 12.7
	Second time	○ 97	● (97) 94 (94→100)	○ 81	R	
R	First time	● (94) 84 (83→100)	○ 84	● (88) 84 (84→100)	Q	1989. 12.9
	Second time	○ 96	○ 84	○ 93	D	

Ways of looking tables

The subject got win the game to the partner in time with percentage right score XX.

The subject lost the game to the partner at the time of percentage progress WW of all problems. His overall right score resulted in XX%, with the right score rate YY% at the time when the partner finished and the right score rate ZZ% afterwards.

Fig. 7 Summary record of progression of conducted experiment.

Fig.9 Eye camera

Fig. 10 Illustration of eye camera to take a pupil image by the illumination of infrared LED.

Fig. 11 Relationship between center of the eyeball and the center of the crystalline lens.

Fig. 12 Block diagram of the realtime image processing unit.

Fig. 13 Number of display presentation and right answer rate versus cycle of display for all the experiments.

Fig. 14 Results of saccade fraction for all the subjects.

Fig. 15 Result of subject R's eye point data in the experiment B2 and B3.

Fig. 16 Calculated results of eye velocity distribution functions of subject R, for all test numbers of experiments B2 and B3.

Fig. 17 (a) Distribution functions for time interval of eye blinking (Subjects P).

Fig. 17 (b) Distribution functions for time interval of eye blinking (Subjects Q).

Fig. 17 (c) Distribution functions for time interval of eye blinking (Subjects R).

Fig. 18 Calculated dependence of F and F_M on presentation rate for all subjects P, Q and R, for all experiments B2, B3 and B4.

Fig. 19 Average heart rate (m) and standard deviation (σ) during experiments B2, B3 and B4 for all subjects P, Q and R.

Fig. 20 Time changes of heart rate in B2, B3 and B4 (subject P).

Table 1 Characteristic parameters for model of human information processor

	δ : Duration time	μ : Capacity	κ : Code type
Perceptual System			
Visual Image Store	200 [70-1000] msec	17 [7-17] msec	Physical
Auditory Image Store	1500[900-3500]msec	5 [4.4-6.2] msec	Physical
Cognitive System			
Short Time Memory	7 [5-226] msec	5 [7-9] msec	Acoustic or Visual
Long Time Memory	∞	∞	Semantic
τ : Cycle			
Perceptual Processing System	100 [50-200] msec		
Cognitive Processing System	700 [25-170] msec		
Motor Processing System	70 [30-100] msec		

Meaning of XX [YY-ZZ] : XX, average value, YY and ZZ, lower and upper ranges of the value

Table 2 Detailed system set up for Side A

Sub-system Name	Items of Measurement and Data Processing
Polygraph (1A96, NEC San-ci)	<ul style="list-style-type: none"> • EEG : 6 electrode pairs $F_{P1}-A_1$, $F_{P2}-A_2$, C_z-A_1 , C_z-A_2 , O_1-A_1 , O_1-A_2 • EOG : 2 electrode pairs Right- and left-sides and upper- and lower-sides of right eye • ECG : Single electrode reduction Left breast V_4 and right breast intercostal collarbone midline • SPR : 2 point electrode Between palm and back of right hand • Respiration : Strain gauge type sensor curve
Eye Camera (Talk Eye, Takei Co.)	<ul style="list-style-type: none"> • Eye mark tracing
Personal Computer for Presenting Cognitive Tasks	<ul style="list-style-type: none"> • Presenting cognitive tasks with voice guides by VDT and VCU • Sending and receiving control command signals and automated data log of experimental steps between PC of side B
Personal Computer for Recording Physiological Sensors	<ul style="list-style-type: none"> • AD converting of physiological data and voice data with sampling rate 250Hz • Displaying realtime traces of AD-converted data, with output of eye pupil data processing system being superimposed on VDT for monitoring purpose

Table 3 Detailed system set up for Side B

Sub-system Name	Items of Measurement and Data Processing
Eye Camera (Eye Mark Recorder, NAC)	<ul style="list-style-type: none"> • Eye mark tracing for left eye • Infrared picture of right eye
Personal Computer for Processing Pupil Picture	<ul style="list-style-type: none"> • 2bit image processing of right eye on extended board • Realtime computing of pupil area and displaying processed data on VDU(Cycle time 1/30 sec)
Personal Computer for Presenting Cognitive Tasks	<ul style="list-style-type: none"> • Same as for Side A

Table 4 Condensed summary of retrospective reports from all subjects

Item	Sub-item	Subject P	Subject Q	Subject R
Impression of problem difficulty order	First time	B4 > B3 > B2	B3 > B2 > B4	B4 > B2 > B3
	Second time	B4 > B3 > B2	B3 > B4 > B2	B2 > B3 > B4
Solving method in the first time	B2	Step-by-step elimination	Step-by-step elimination	Step-by-step elimination
	B3	Step-by-step elimination	Identity P,L,E key first	Identity P,L,E key first
	B4	Imaging state transition model	Imaging state transition model	No idea of rules, random solving
Improvement of solving method in the second time	B2	Same as first time	Same as first time	Same as first time
	B3	Identity P,L,E key first	Same as first time	Same as first time
	B4	Tried to remember transition rule matrix but in vain	Same as first time	Same as first time and save the information quantity to be remembered
Effect of information change speed in the second time	B2	1sec is too fast to follow	1sec is irritating	1sec is too fast to follow
	B3	1sec is difficult to solve	1sec is difficult	The slower, the better
	B4	1sec is too fast to confirm	1sec is disturbed by non-attended shape change	Difference in speed in no hindrance in solving
Competition effect in the first time	B2	Disappointed when loosed	Kept my own pace after defeat	No special feeling
	B3	Very irritated after defeat	Felt "pressure"	Thought to go steadily
	B4	anxious about other person's rating because of too bad performance	Felt "superiority" because I won	I wished to finish it soon after defeat

Photo 1 The image photo of eye pupil.

Photo 2 Eye point indicated as '+' mark superimposed on subject's front view image.

Photo 3 Method of setting frame window.

Photo 4 Time-varying graphs as superimposed on picture of subject's front view.

Photo 5 Picture of developed unit as extended board for personal computer.

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