Neuropsychological Aspects Observed in a Nuclear Plant Simulator and Its Relation to Human Reliability Analysis

Chapter · January 2017

DOI: 10.1007/978-3-319-41950-3_13

5 authors, including:

Andre Pinheiro
University of São Paulo

Marcelo Ramos Martins
University of São Paulo

July Silveira Gomes
Universidade Federal de São Paulo

Enrique López Droguett
University of Maryland, College Park

Advances in Intelligent Systems and Computing 495

Sacit M. Cetiner
Paul Fechtelkotter
Michael Legatt *Editors*

Advances in Human Factors in Energy: Oil, Gas, Nuclear and Electric Power Industries

Proceedings of the AHFE 2016 International Conference on Human Factors in Energy: Oil, Gas, Nuclear and Electric Power Industries, July 27–31, 2016, Walt Disney World®, Florida, USA

Springer

Neuropsychological Aspects Observed in a Nuclear Plant Simulator and Its Relation to Human Reliability Analysis

André Ricardo Mendonça Pinheiro, Eugênio Anselmo Pessoa do Prado, Marcelo Ramos Martins, July Silveira Gomes and Enrique López Droguett

Abstract This paper will discuss preliminary results of an evaluation methodology for the analysis and quantification of errors in manual (human) operation by training cognitive parameters and skill levels in the complex control system operation based on Neuropsychology and Psychophysiology approaches. The research was conducted using a game (nuclear power plant simulator) that simulates concepts of operation of a nuclear plant with a split sample evaluating aspects of learning and knowledge in the nuclear context. Operators were monitored using biomarkers (ECG, EEG, GSR, face detection and eye tracking) and the results were analyzed by statistical multivariate techniques. The experiments aimed at observing state change situations such as shutdowns and planned matches, incidents assumptions and ordinary features of operation. The preliminary findings of this research effort indicate that neuropsychological aspects can contribute to improve the available human reliability techniques by making them more realistic both in the context of quantitative approaches for regulatory purposes as well as in reducing the incidence of human error.

A.R.M. Pinheiro (✉) · E.A.P. do Prado · M.R. Martins
Analysis, Evaluation and Risk Management Laboratory,
Departamento de Engenharia Naval, University of São Paulo,
São Paulo, SP, Brazil
e-mail: andrericardopinheiro@usp.br

E.A.P. do Prado
e-mail: eugenio.prado@labrisco.usp.br

M.R. Martins
e-mail: mrmatins@usp.br

J.S. Gomes
Laboratório Interdisicplinar de Neurociências Clínicas,
Federal University of São Paulo, São Paulo, SP, Brazil
e-mail: july.flp@gmail.com

E.L. Droguett
Department of Mechanical Engineering, University of Chile, Santiago, Chile
e-mail: elopezdroguett@ing.uchile.cl

S.M. Cetiner et al. (eds.), *Advances in Human Factors in Energy: Oil, Gas, Nuclear and Electric Power Industries*, Advances in Intelligent Systems and Computing 495, DOI 10.1007/978-3-319-41950-3_13

Keywords Human factors · Human-systems integration · Neuropsychology · Psychophysiology · Human reliability analysis · Incidence of human error

1 Introduction

The neuro scientific study of human behavior has advanced greatly in recent decades and today is an invaluable tool for studying human behavior in various situations. It also allows the dealt with limitations of available methods for analysis of human factor contribution to complex control system operation by identifying and evaluating factors involved in decision making, such as the influence of ergonomic elements in the criteria of acquired skills (training) and cognitive load.

An important component in the evaluation of complex systems is the human reliability during operation. Human reliability refers to the probability of the human element of performing the scheduled tasks during a defined period for system operation when tested under specified environmental conditions.

Cognitive ergonomics refers to mental processes such as perception, memory, reasoning and motor response, affecting the interactions among humans and other elements of a system. Relevant topics include the study of mental workload, decision making, specialized performance, man-machine interaction, stress and training as well as correlation between designs involving complex operating systems and human operator.

Taking into account the difficulties imposed by the human profile, the use of cognitive monitoring equipment is an interesting option for the full assessment of training and operating procedures, as it is possible to identify and record the patterns of cognitive skills in each operator as face attention, reaction ability, level of knowledge and motor actions, which may be later assessed by a monitoring group composed of the most experienced operators, psychologists and engineers linked to the process.

After evaluating operators via the application of the proposed methodology, the collected information can be used in a Human Reliability Analysis. In particular, through the analysis of Eye Tracking, EEG (electroencephalogram), ECG (Cardiac Monitoring) and GSR (Galvanic Skin Response) data, a model of the operator flow experiences will be developed allowing us to increase the operator performance to a higher level of human reliability.

To reach this end, it is necessary to observe moments of high workload, when there is a higher probability of micro incidents.

This research was conducted using a game (Power Plant Simulator) that simulates concepts of operation of a nuclear power plant with a split sample to evaluate aspects of learning and knowledge in the nuclear field. Operators were monitored using biofeedbacks (ECG, EEG, GSR, and eye tracking), and the results were analyzed by multivariate statistical techniques. The research has two main objectives:

1. Identify biomarkers (cognitive and psychophysiological variables) that influence the behavior during the decision-making process on tasks with situations of risk and uncertainty involving a group of operators in a virtual control room of a nuclear power plant simulator;
2. Establish preliminary protocol Neuropsychology and Psychophysiology assessment to be used in studies of human reliability for operations in complex hybrid systems.

2 Methodology

For decision-making experiments, we used a game that partially reproduces the control room of a simulated nuclear power plant in 2D computing environment. Game's basic idea is to produce sufficient electricity to lite a whole city without causing a Nuclear disaster. The procedure is performed by the increase or decrease of the control bar to start the nuclear reaction in the reactor. It is crucial to find the right combination of settings to produce energy not damaging the reactor components for exceeding its limits of operation, knowing that all reactor components have their pre-determined limits. If you exceed them and not perform contra measures, the reactor will be damaged, which will appear in the Repair Facility section of the game. If any of the components of the reactor oscillate the condition 'Warning' should rapidly reduce the slider that caused the condition. While the "warnings" (Warning) in oscillation, will damage the proper components. In the repair installation, this damage is indicated in two forms. Beyond ways to produce electricity to supply the energy demand, it should also generate profit. There are various expenses acquired during the game, especially early in the game. These costs are called Aux Power and appear in the financial section.

For the experiment the operators were divided in four groups:

- G1—High levels operators. Individuals that know nuclear aspects of a power plant and that get used to deal with IHM (Human Machine Interface);
- G2—Individuals that know nuclear aspects of a power plant but do not get used to deal with IHM (human machine interface);
- G3—Individuals that do not know nuclear aspects of a power plant but have a good ability with IHM (human machine interface)—game simulation;
- G4—Individuals that do not know nuclear aspects of a power plant and do not have a good ability with IHM (human machine interface).

The grouping was based in classical technique of questionnaire and formal test with a follow up of psychologist and a nuclear engineer with experience in nuclear power plant operation (Fig. 1).

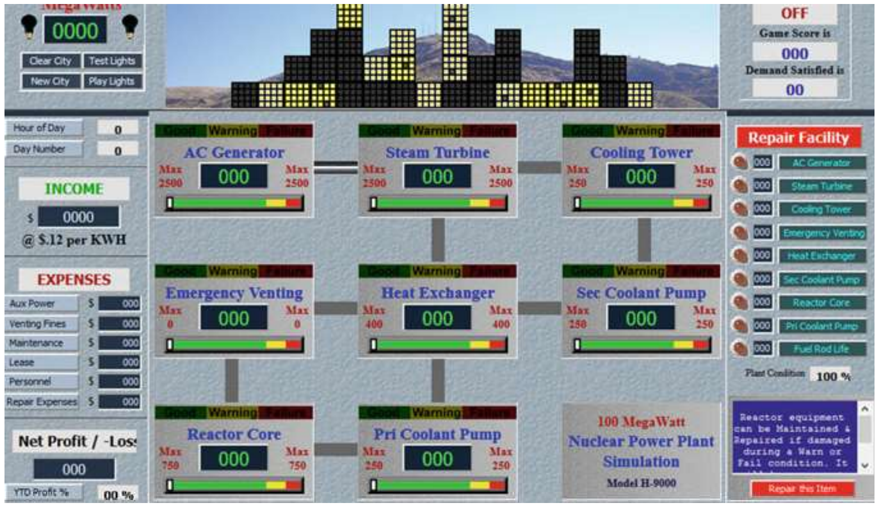

Fig. 1 The display with the variables utilized to control the nuclear reactor. *Source* http://www.nuclearpowersimulator.com/ [1]

The operator was subjected to three conditions in sequence, with sub-conditions, as described below:

1. Baseline: eyes closed and eyes open;
2. Cognitive tasks: selective attention, visual-spatial working memory and arithmetic evaluated from the cognitive assessment battery ProA;
3. Nuclear power plant simulator in a 2D computing environment (operation—events triggers).

All operators played the game two times in a continuous test and the following bio signals were recorded: GSR (Galvanic Skin Response); HRV (Heart Rate Variability); Eye Tracking, and EEG (Electroencephalography).

The individuals were grouped based on their performance, and it was constructed a matrix in which the following were analyzed on a multivariate regression:

- Rule–Based Learning (RBL)
- Knowledge in the nuclear area (KNA)
- Skills on HMI or game (SBG).

According Reason [2], the error is directly associated with performance levels as shown in Fig. 2.

Aiming to merge and link the various levels of knowledge, skill and rule with the performance and mistakes, the groups were analyzed individually comparing individuals within each control group.

After the identification of differences and similarities in operation (action) between the operators of each control group and the identification of possible

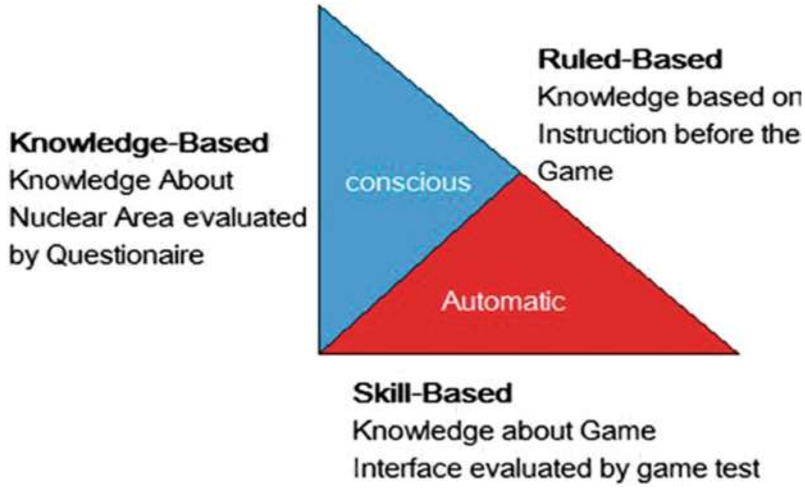

Fig. 2 The continuum between conscious and automatic behavior (Adapted from [2])

Table 1 Performance numerical classification

Performance	Numerical classification
Rule (R)	1-Yes/0-No
Knowledge (K)	1-Yes/0-No
Skill (S)	1-Yes/0-No

patterns of each level of performance, it was provided a binary sequence (RKS) based on Table 1. This sequence indicates the level of performance of each operator in its characteristics.

How operators receive the same set of instructions before the game, the basement rule was considered equal to 1 for all groups. Leaving assess only performance with bases in the knowledge and skills of operators. To characterize the groups and classify each individual by areas of knowledge and skill it was used a questionnaire with questions about the professional and academic activities of each individual, as well as an interview with each individual before the collection procedure. Therefore, individual performance is related to the foundation as a rule, specific knowledge and skills linking stressors moments that can compromise the operation to change patterns provided by bio-signals. Subsequently the operation, the following equations were developed to identify the influences based on rule (RBL), performance based on knowledge in the nuclear field (KNA), and skill based on knowledge of HMI or game (SBG), considering each operator. To treat it numerically, It was used a multivariate regression based on least squares method.

$$X\beta + \varepsilon = Y \tag{1}$$

$$\begin{bmatrix} 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} RBL_{G1} & RBL_{G2} & RBL_{G3} & RBL_{G4} \\ KNA_{G1} & KNA_{G2} & KNA_{G3} & KNA_{G4} \\ SBG_{G1} & SBG_{G2} & SBG_{G3} & SBG_{G4} \\ 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} R_{G1} & 0 & 0 & 0 \\ 0 & R_{G2} & 0 & 0 \\ 0 & 0 & R_{G3} & 0 \\ 0 & 0 & 0 & R_{G4} \end{bmatrix} \quad (2)$$

Based on the results, this study aims to quantify the percentage of evolution between operations (1) and (2) and their relationship with each of the biological signals, characterizing operators and groups. Performance was measured by an in game function that displays the profit generated by the operator over the task.

3 Results

3.1 Regression Based on Performance Data

The results presented in Table 2 can identify the weight of each level of performance by group. Equation (1) was developed by multivariate regression analyzing the result of the β coefficient that was normalized in percentage. The evolution of an operation was calculated by comparing game tasks 1 and 2 total profit.

The above results show the performance variation in both game activities, considering the groups division proposed by knowledge, skill and rule.

Table 2 Result from multivariate regression based on operator performance divided per group

Game 1				Game 2			
Group	RBL (%)	KNA (%)	SBG (%)	Group	RBL (%)	KNA (%)	SBG (%)
1	10	60	30	1	18	50	32
2	20	80	0	2	25	75	0
3	50	0	50	3	30	0	70
4	100	0	0	4	100	0	0

Performance improvement game 1–2	
Group	Improvement (%)
1	+16
2	+60
3	+95
4	+65

Fig. 3 Example of normalized GSR data from an operator during a game

The methodology presented can be applied in an operator training to be a tool to identify relevant aspects in a training individualization that depends on the level initially presented by the individual. Therefore, an individualized standard in performance based on training could reduce or increase the hours of training in certain groups depending on the knowledge of the individual.

The percentage of each performance level when analyzed by the control group has close patterns in bio signals among its individuals during operation, providing evidence on the mistakes and missteps committed by systemic pattern of bio signals per group when analyzed a specific error type. In following results will be better explained.

Even comparing directly related individuals between groups and individually, according to the performance levels we can classify the influence of each of the decision-making standards, including the technical and behavioral analysis of each individual.

3.2 Results from Bio Signals Data

During the experiments, the bio signals (GSR, temperature and HRV) data from each individual was collected from J&J hardware [3] analyzed with the bio explorer package.[1] In order to allow the comparison among different individuals in different groups, the data was normalized using the individual base line.

The signal obtained from the GSR sensor (Galvanic Skin Response) can be a very useful data to identify error during the operation. Figure 3 shows GSR variation from the operator during game.

The game it is possible to correlate warnings, errors or missteps committed by operator with peak of normalized GSR response.

The observation considers a peak as a variation at least 15 % greater than the previously value observed. This criteria were considered to analyze the collect data

[1]Bio-Explorer is a Windows program for real-time biophysical data acquisition, processing, and display. It is intended for personal use in entertainment, education, and experimentation.

and to provide a correlation with stress condition during an operation. Other important result is the duration of peak; The failure event usually ends when the problem observed after the warning, or the observation (of fail eminence) of an operator results in a counter measure adopted by the operator itself that normalizes the system. After the operator solved the problem, the stress stimulation disappears and the GSR signal reduces to the previous level.

The use of HRV (Heart Rate Variability) is not direct as GSR. The possibility to use HRV with others sensor is aim of futures studies. Prospective analyses to correlate EEG with HRV have been conducted by the authors.

3.3 Results from Eye Tracking

The principle of the eye tracker is the analysis of eye movement to assess subconscious cognitive processes. The method of analysis is done with the monitoring of eye movements using an infrared reflected light in the eye and then through a geometric model, it is determined the exact look of the attachment point. To assess the patterns of eye movement and fixation of the look, can be used the “heat map” that shows how much attention is directed to the menu, or the “plot gaze” which shows the pattern of visual user research before making a decision.

The principle of the eye tracker is the analysis of eye movement to demonstrate subconscious cognitive processes. The analysis method is done with the tracking of eye movements via infrared sensors, then applies a geometric model, given exactly the visual fixation point. To assess the movement patterns of the eyes and look fixation, its used a “heat map” or gaze plot that indicates how much attention is directed to activity, indicating the standard visual user review before making a decision. In developing the methodology proposed by the research, the use of this visual focus monitoring equipment allows the extraction of a large amount of relevant information about the error (failure) as levels and focus of attention, time and error types (failure), operating standards.

Another important point is the ability to quantify the level rule (reading time and steady focus on the task) based on the instruction provided to all operators equally as a factor to quantify performance levels, on closer analysis the individual error of investigation SKR following the criteria developed by Reason [2] used in the methodology.

Considering qualitative analysis of data provided by eye tracking, the same group individuals have a small variation of visual focus on operating instruments. This variation has shown the weight of each performance level in the decision-making cycle in relation to the focus of attention in control instruments according to each operators group. For example:

The control group 111 (level of rule-knowledge-skill) showed no significant change of focus in the instruments remaining faithful to the operation pattern based on their performance levels, varying only in intensity in a different game. Below the example of high-level operation pattern that can determine a standard to compare others operators. That pattern is a result of good rule-knowledge-skill based learning (Fig. 4).

Analyzing the group 110 (level of rule-knowledge), it presented a unique variance focus on instruments just by changing the operation pattern of trying to fix problems encountered by lack of skill (simulation and games) considering the user level of performance (SKR), thereby undermining the effectiveness of the group control system operation (Fig. 5).

Considering the group 101 (level of rule-skill), its operator showed significant variations focus on instruments ranging around 2–3 instruments for the operation in order to remedy problems caused by lack of performance level knowledge in the nuclear field (Fig. 6).

Fig. 4 Gaze plot control group 111-Pattern game 1 and game 2

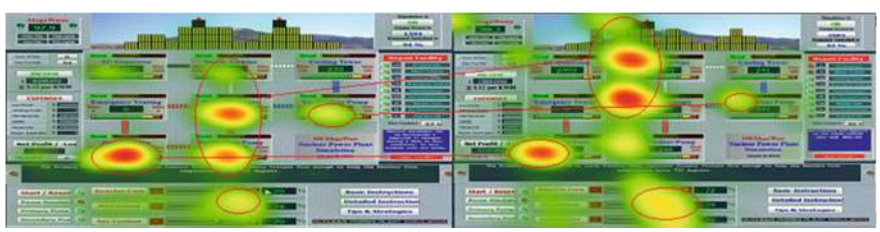

Fig. 5 Gaze plot control group individual 110-Pattern game 1 and game 2

Fig. 6 Gaze plot control group 101-Pattern game 1 and game 2

Fig. 7 Gaze plot control group 100

Finally, the group 100 (level of rule) showed the worst result among the four control groups, ranging several times the visual focus on the control instruments. This is due to lack of basis of performance levels (Fig. 7).

The Eye tracking was a useful tool to identify of operation based on gaze plots pattern of performance. There was a decreasing focus point when analyzing from groups 1–4. It is possible to quantify how much a lack of one level of performance impact in operation performance crossing the data of Table 2 and results from eye tracking. In this game, a good performer has 6 focus points in correct place; the knowledge level guide to identify and the skill level guide to transform this knowledge in correct action.

3.4 Results from EEG

The electroencephalogram (EEG) was continuous recorded by a 19 channels elec-trode cap (Electro-Cap International Inc.), according to the 10–20 International Elec-trode Placement System on a 24 channel MITSAR 202 EEG machine [4] in a monopolar montage referenced to linked ears. The EEG was recorded for 5 min for either eyes open and eyes closed condition and continuously for all the cognitive tasks and during the simulation as well. The recording bandwidth was 0.5–70 Hz with a notch filter from 55 to 65 and sampling rate of 250 Hz. The data was analyzed using WINEEG software, and the off-line artifacts' removal procedures was followed. Artifact correction was done using independent component analyses tool (ICA) to correct eyes blinks and eyes movement artifacts, followed by a visual inspection of the EEG signals to remove remaining artifacts. A Fast Fourier transform was used to separate the frequency bands and the absolute power (AP = μV2) was calculated for the following bands: Theta: 4–8 Hz, Alpha: 8–12 Hz, and Beta: 12–21 Hz) due to their importance when investigating cognitive load.

For this paper purposes, i.e. setting up a methodology to verify EEG changes associated to operator failure, the analyses were run individually for each subject comparing the mean difference on spectra activation from 30 s before an error occurrence to 30 s following it. The error occurrence presented here was Primary Coolant Pump flashing light alarm. As an example, Fig. 8 shows the difference in the activation pattern of four subjects (G1, G2, G3 and G4), one from each group. Each subject has 3 maps, representing the 3 frequency bands analyzed.

From Fig. 8, it is possible to see different EEG activation patterns associate to the same error at the same task: while some operator increase theta (G1 and G3), which reflects information processing usually associated to encoding new information, G2 didn't show differences in this pattern, due less information process. In the other hand, a decrease in alpha activity, observed in the G2 operator, is usually associated to in-crease cognitive load and task difficulty. Considering that G2 was from the group of individuals with a higher knowledge on nuclear power plant, but not on IHM, this pre-analysis draws attention to the importance of the subjective and individual variables associated to the operator performance, instead of relying solely on knowledge.

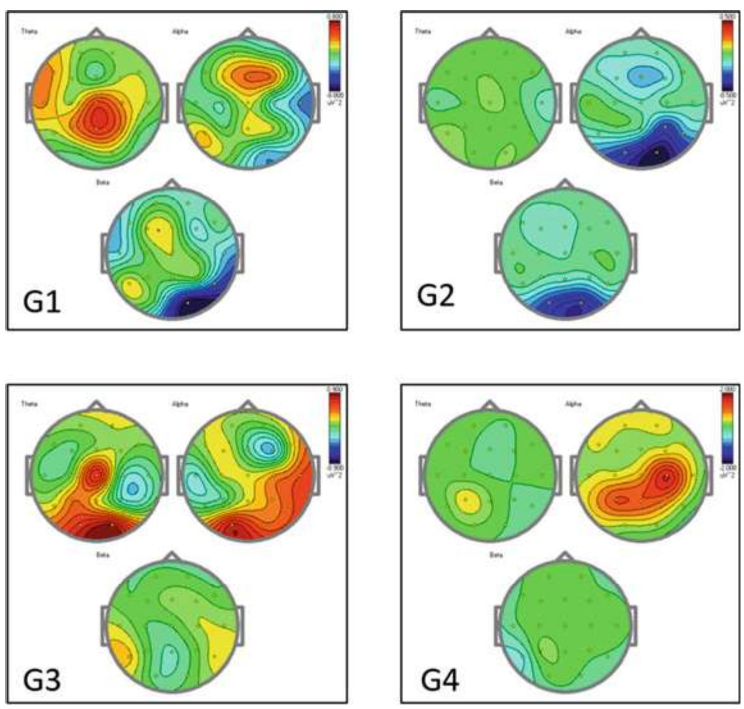

Fig. 8 Scale ranges from *blue* to *red* meaning respectively decreasing or increasing in individual EEG brain pattern (deactivation or activation) from 30 s pre event to 30 s post event. Note that *G1*, *G2*, *G3* and *G4* have different power scale, based on the individual magnitude of the changes. *Green* colors represent non-significant differences

4 Conclusion

This research that aims to correlate the bio signals with error analysis is only in its begging stage. The proposal tries to establish a classification standard based on performance to figure out which characteristic of a group of operator are relevant to find the better characteristic to development the pattern that are suitable to operation.

Based on this initial issues are possible to qualify good information provided by eye tracking. Comparing the results, it was possible to establish a pattern of good operation.

The use of GSR allows the identification of stress condition and how each operator handles the situation when it is necessary an intervention. The current study found a peak variation on GSR signal during an individual stress condition that suggests the needs of special attention to solve the problem and further studies will try to correlate response time with normalized GSR values to better understand this psychology behavior.

Finally, the prospective use of EEG shows a brain activation area array per group of operators and allowed linking the measurement with proposed classification for a specific error (primary coolant bomb) for all operators.

References

1. Nuclear Power Simulator-Game, Majik Mike Simulators. Information, http://www.nuclearpowersimulator.com
2. Reason, J. (1990). Human Error. Cambridge University Press
3. Software J&J Engineering, J&J Engineering. Inc. Information, http://jjengineering.com
4. Software Mitsar - EEG systems, Mitsar Medical, Petersburg, Russia. Inc. Information http://mitsar-medical.com