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Effective attention allocation behavior and its measurement: a preliminary study

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Abstract

In general, evaluation of human–machine interface design remains a challenging task. Specifically, there remains a lack of method for tracking effective human operator's attention. This paper presents a study aimed at devising such a method. This method is based on a combination of operators' eye movement and hand movement behaviors. The eye movement reflects the operators' cognitive process and attention allocation, while the hand movement reflects the operators' physical action, which is the result of a cognitive process. Effectiveness of that piece of cognition (eye movement) can therefore be evaluated based on the result of an action (hand movement). The said measure, which may be called the hand–eye measure, is examined for its sensitivity to a good or poor operation behavior and patterns that are further correlated to the operator's behavior and performance. At present, the patterns across the whole operation period are explored. A reference system is employed to validate the hand–eye measure.

Keywords: Human–machine interface evaluation; Human–computer interaction; Attention allocation; Measurement; Eye movement; Hand movement

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1. Introduction

Evaluation of a human–machine interface remains a challenging task. One of the issues in evaluating an interface is whether and how a particular piece of information on an interface display is effectively used by human operators. In literature, this kind of evaluation is largely conducted by measuring the operator's performance. Such a performance-based method is based on the following assumption: given two interfaces (A, B) with different pieces of information displayed on them (respectively), if performance on A is better than that on B, the information displayed on A is more effectively used than that on B (i.e. A is more effective). Such a method may also be called product measure in the sense that the end result (i.e. performance in accomplishing a task) is used for inferring the process. Studies regarding the ecological interface design (EID) framework are more or less based on this method (Janzen and Vicente, 1998; Vicente et al., 1995). These studies also appear to follow such a logic cue as: the longer duration or the higher number of eye fixation on an information variable, the more attention on it; further, if in this case the corresponding trial also shows performance improvement, then a positive indicator or correction between the use of that piece of information and the performance can be established. The problem with this kind of idea is that higher attention may not necessarily imply a more effective use of that piece of information. Information of operator's screen activities was used by Janzen and Vicente (1998) to understand operator's attention allocation behavior. The screen activity makes more sense of results of a cognitive (attention) process; yet not much sense of the cognitive process itself. So the screen activity alone cannot be used to evaluate the cognitive process. Another popular method for evaluating effectiveness of information on an interface display is subjective rating or commenting by operators either during or after a trial. It is known that the subject rated method generally suffers from uncontrollable errors that are relevant to uncertainties in judgment due to the emotional nature with human beings. Therefore, the issue of measuring an effective cognitive process remains to be open.

A study presented in this paper proposed a new measurement method, which was based on a combination of the measurements of two classes of operator behaviors: the action class and the thinking (or attention allocation) class during the course of operation. In the particular context of application considered in this study (i.e. interfaces for a process plant), the operator's mouse clicking was used to measure the operator's action, while the operator's eye movement was used to measure the operator's attention. This new measurement method or measure may be called the hand–eye measure. The hand movement should imply more about the action of an operator, which is subsequently the result of a cognitive process (or thinking) of the operator. By combining these two, one should be able to get insight into effectiveness of that particular thinking. Therefore, the study hypothesized that (i) the eye movement does not follow the same pattern as the hand movement, and in other words they work independently to form a process of thinking-and-doing; (ii) patterns that describe their relationships are sensitive to good or poor operation performances; and (iii) patterns that describe their relationships are sensitive to different interface designs. The three hypotheses are, respectively, denoted as Hypotheses (i), (ii), and (iii). To test these hypotheses, a published study on the experimental comparison of two interfaces (Lin et al., 2003) was employed. Specifically, operator's behaviors on these two interfaces were known, and thus they can serve as a basis for evaluating effectiveness of the hand–eye measure.

There is a general remark on using eye movement parameters. There have been several studies using the eye movement derived parameters based on the fact that the mental processing and arousal mechanism can be observed in visual behavior, where the eyes play an important role in interacting with the interface through viewing the display (Hess et al., 1998). In our work, we used one of the eye movement parameters, namely, eye fixation. Usually the eye fixation was used to indicate the mental workload; see (Backs and Walrath, 1992). However, at the present study, we used the eye fixation as a means of tracking the operator's cognitive process, as when the eyegaze point falls onto a particular variable on an interface display medium, it is reasonable to say that the operator's attention is paid on this variable. There are several excellent studies on using the eye movement parameters to understand the operator's cognitive process, notably (Goldberg and Kotval, 1998; Moray and Rottenberg, 1989). Primarily, their experiments were performed on scenarios which required only a short period of recording the eye movement behavior, e.g. 60 s in (Moray and Rottenberg, 1989). Our experiment lasted much longer, up to 8 min, which allows us to examine the eye movement behavior for a more complex application scenario and an intertwined physical–physiological process. The eye fixation and pupil diameter parameters are frequently used in characterization of the operator mental workload; see our previous work in evaluating interfaces (Lin et al., 2003).

The organization of the paper is as follows. Section 2 describes the example used in this study. Section 3 gives a detailed description of the experiment set-up. Section 4 shows results of the experiment. Section 5 discusses the results of the experiment with some implication of this new measurement technique. Section 6 concludes the paper and discusses the future work.

2. A case: the DURESS plant

A thermal–hydraulic process plant system called the dual reservoir system simulation (DURESS) is taken as an example. DURESS was initially prototyped (Vicente and Rasmussen, 1992) for illustrating and validating the ecological interface design framework. The structure of the DURESS plant system can be simplified and represented by a diagram shown in Fig. 1. In Fig. 1, VA and VB stand for input valve control, PA and PB for pump control, R for reservoir, VO for output valve control, H for heater control, T

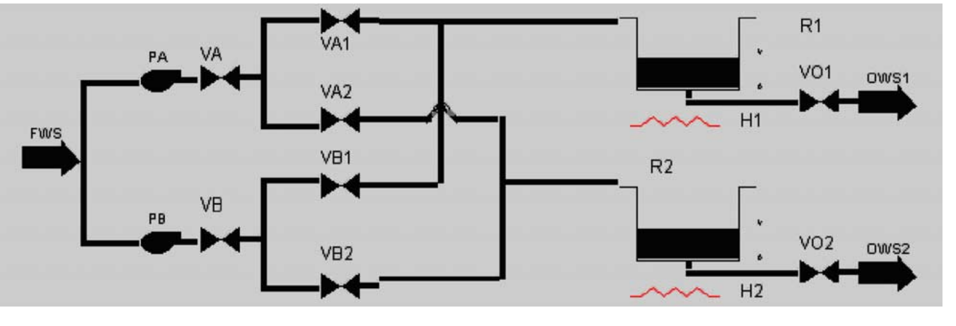


Fig. 1. The schematic diagram of the DURESS plant.

for temperature indicator, FWS for the feed-water stream, and OWS for output water stream. The process of DURESS can be described as follows: The FWS is fed into the plant, split into two streams, emerging out of Reservoirs R1 and R2, respectively, forming into two output water streams (OWS1, OWS2). The goal of the process control is to make certain state variables achieve their desired objects, namely (1) *Object 1*: the desired temperature of OWS1: 40 °C; (2) *Object 2*: the desired temperature of OWS2: 20 °C; (3) *Object 3*: the desired mass flow rate of OWS1: 8 kg/s; and (4) *Object 4*: the desired mass flow rate of OWS2: 2 kg/s. The following assumption was made for the plant operation: At PA (PB), VA (VB), VA1 (VA2), VB1 (VB2), R1 (R2), H1 (H2), and VO1 (VO2), sensors were in place to measure the actual physical behavior, respectively, i.e. pressure (related to the pump), flow rate (related to the valve), level of water (related to the reservoir), and temperature (related to the heater).

3. Methods and materials

3.1. Two interfaces for DURESS

Two interface design frameworks have been proposed in literature: one is called the ecological interface design (EID) framework (Vicente and Rasmussen, 1992) and the other

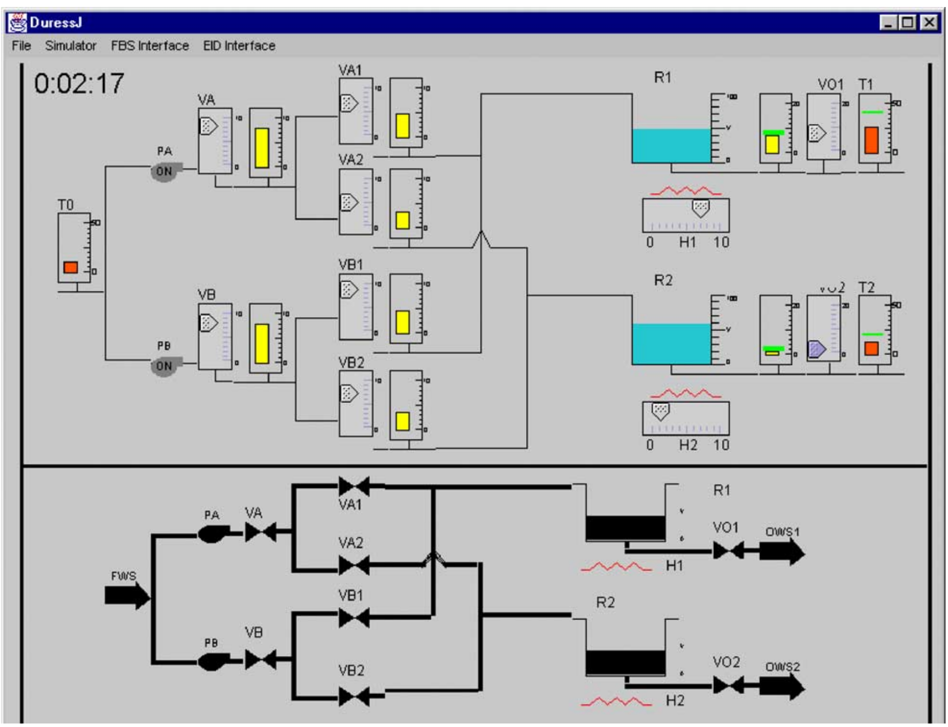


Fig. 2. FBS-DURESS interface.

is called the function-behavior-state (FBS) framework (Lin and Zhang, 2003). Both frameworks aim to provide principles for determination of information content on an interface display; i.e. to answer the question: what information is needed for a work domain (the process plant in this case). Both frameworks achieve this aim by providing methodology for work domain analysis. At this point, the EID framework asserts that a domain can be modeled by the following concepts: the functional purpose, the abstract function, the generalized function, the physical function, and the physical form. Instead, the FBS framework asserts that a domain can be modeled by the following concepts: the structure, the state, the behavior, the function, the principle, and the effect. The definitions of these concepts are not discussed here and can be found in (Vicente and Rasmussen, 1992; Vicente et al., 1995 for EID; Lin and Zhang, 2003 for FBS). In particular, in (Lin et al., 2003), there is a comparison of these two frameworks based on an experiment.

Based on the frameworks, two interfaces for the DURESS plant were implemented and are called FBS-DURESS (Fig. 2) and EID-DURESS (Fig. 3), respectively. These figures also give some impression of how those concepts are displayed conceptually. Note that the interface form design is not considered here, though they can affect the operator's cognitive process. In order to eliminate such effects, these two interfaces were made in

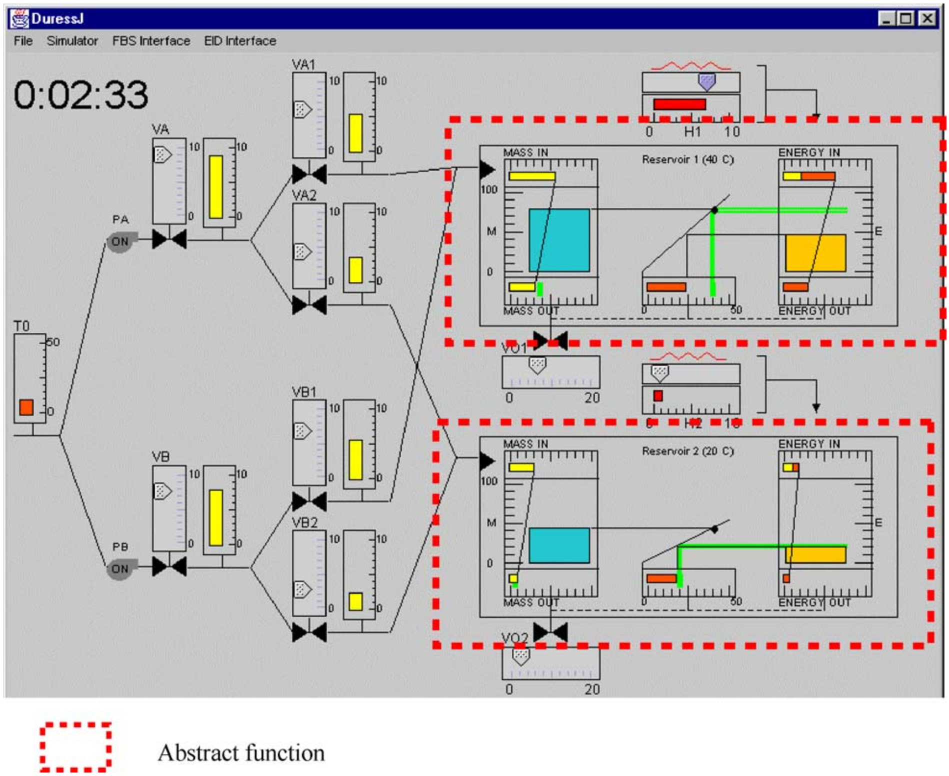


Fig. 3. EID-DURESS interface.

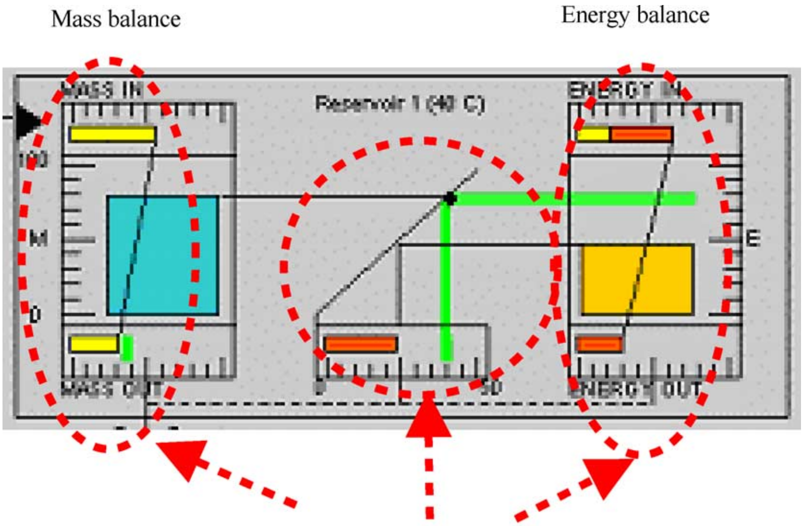


Fig. 4. The abstract function in EID-DURESS interface.

a very similar look-and-feel form. The forms of visual items on the interface displays are mostly self-explanatory.

Among many other differences, the most important one between these two interfaces lies in the concept called the abstract function in the EID interface (see Fig. 3). The abstract function concept was defined as the causal structure of the process in terms of mass, energy, information, or value flows (Vicente and Rasmussen, 1992). Its visual representation is further shown in Fig. 4, where the seesaw-like icons graphically indicate the states of mass balance and energy balance. Particularly, the vertical position of the seesaw-like bars represents the states that mass and energy are balanced in the storage component-tank. The principle concept in the FBS framework may correspond to the abstract function in the EID framework. For the normal control and monitoring tasks, the FBS interface does not display the principle concept, while the EID interface always display the abstract function concept no matter what operation tasks are. One of the hypotheses in the study reported in (Lin et al., 2003) is that the EID interface with that graphical icon degrades the operator's performance yet increases the operator's mental workload.

In order to be able to capture the operator's cognitive process and physical process on the level of individual component (plant) or individual variable (interface model or interface), the FBS interface and the EID interface were divided into several regions (see Figs. 5 and 6, respectively) with which variables are differentiated. It is noted that in some cases, two variables are not geographically separated, and consequently one region may bound two variables. The division of regions and corresponding variables are described as follows (the EID interface; Fig. 6): Region 1 bounds PA and VA, Region 2 bounds PB and VB, Region 3 bounds VA1, Region 4 bounds VA2, Region 5 bounds VB1, Region 6

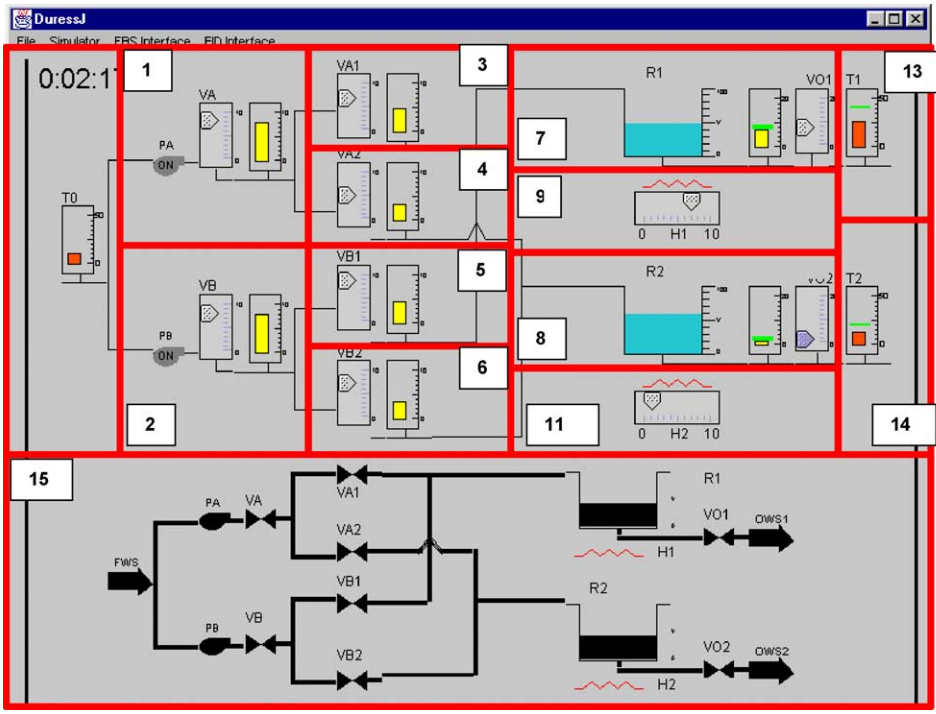


Fig. 5. Divisions of FBS-DURESS interface.

bounds VB2, Region 7 bounds R1 (mass balance) and VO1, Region 8 bounds R2 (mass balance) and VO2, Region 9 bounds H1, Region 10 bounds abstract function, Region 11 bounds H2, Region 12 bounds abstract function, Region 13 bounds energy balance 1, Region 14 bounds energy balance 2. For the FBS interface, the number for each region may correspond to different variables.

3.2. Experiment design

A factorial design of experiment with a randomized complete block design (Montgomery, 2001) was employed for the present study. There are two within-participants factors: interface and scenario. The interface factor was designed to have two levels: function-behavior-state (FBS) interface and the ecological interface design (EID). Details of these two interfaces are seen in later discussions. The scenario factor had four levels: L01, L02, F01 and F02. Among the four levels of scenario, L01 and L02 are normal scenarios (which means that a plant system works well, and the operational goal can be reached if the operator runs the plant correctly), and F01 and F02 are abnormal scenarios (which means that a plant is out of order, and a fault detection procedure is required from operators). Both the normal scenarios (L01 and L02) and the abnormal scenarios (F01 and F02) were designed with different task difficulty levels in mind; specifically, L02 is more

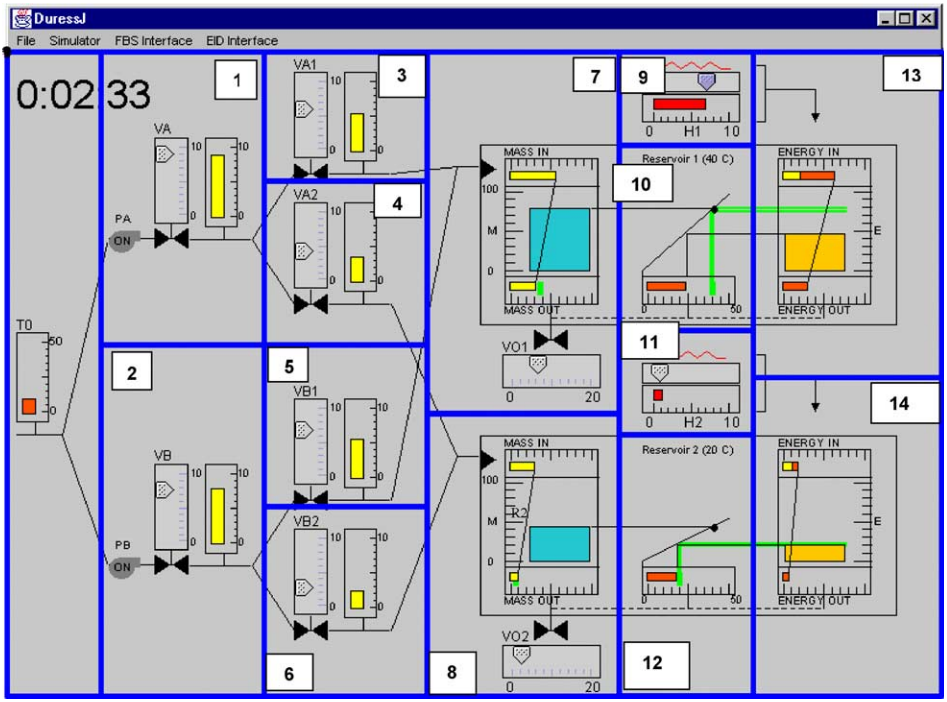


Fig. 6. Divisions of EID-DURESS interface.

difficult than L01, and F01 is more difficult than F02. As a result, the total number of treatments is 8 (2×4).

There were 20 students (6 female and 14 males) from the University of Manitoba involved in the experiment. All of them had an engineering background. The participants were required to perform three replications for each trial, so each of them performed 24 trials in total. In the present study, the participant factor was out of the range of interest and was considered a nuisance factor. Through a blocking technique, the potential effects of operators on the statistical comparisons among treatments could be systematically eliminated. 20 blocks (operators) were considered necessary for this experiment. As a result, in total there were $24\times20=480$ runs for the entire experiment. The other effects, e.g. the order of the operation of interface, etc. were also eliminated through the complete randomization of treatments within blocks. In addition, in order to eliminate possible 'contamination' due to the order of interface, participants were further divided into two groups (half of the participants in each group). One group proceeded with the EID interface first and the other with the FBS interfaces first.

3.3. Apparatus

An eyegaze development system hardware from LC Technologies was used. Two programs for EID-DURESS and FBS-DURESS run simultaneously in one PC.

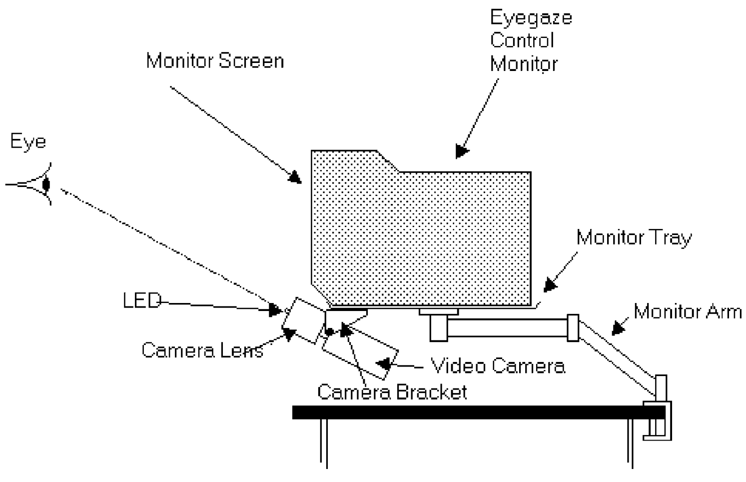


Fig. 7. Configuration of eyegaze system.

The configuration of the eyegaze system is shown in Fig. 7. The video camera is located below the computer screen, and it continually observed the participant's eye. A small, low power, infrared light emitting diode (LED) located at the center of the camera lens illuminated the eye (LC technologies, 2000). The field of view of the eyegaze system camera is approximately 38 mm wide, 30 mm high, and 38 mm back and forth (or as long as the participant is looking within about 40° of the camera *Z* axis). The eyegaze tracker is not head-mounted; therefore, a change in the position of the participant's head will affect a correct tracking of the participant's eyegaze (e.g. if the participant moves his/her eye outside the camera's field of view, the system does not detect a pupil and thus the associated corneal reflection). For this particular application, in order to protect against a change in position of the participant's head relative to the video camera, and further affect a correct tracking of the participant's eye or even result in a failure in tracking because the participant's eye would be out of the field of view of the camera, an accessory was used to 'fix' the participant's head while his/her eye movement behavior is being tracked. When a participant operated the computer, he or she was required to sit back against the wall. Consequently, the position of the participant's eye with respect to the PC monitor screen, where the application program is running could be fixed. However, it was noticed that with such a helmet, participants could easily become fatigued. This was actually one of the reasons that the trial duration was short (maximum 8 min for each trial in the present study).

The eyegaze system shakedown and testing included the following procedures: (1) the positioning of the participants (or the positioning of the monitor tray such that the participants were between 559 and 711 mm distance away from the screen, and their eye level was aligned with the top edge of the monitor screen); (2) the adjusting of the camera (it is recommended by the manufacturer that the focus ring of the lens be set to the maximum value of 1.3); and (3) calibration for each participant. This included two steps. Step 1: the participant gazed at a sequence of dots, and the participant's gaze point on the screen was predicted; Step 2: the participants were adjusted to reduce the discrepancy between the actual position of the dots on the screen and the eyegaze point on the screen until sufficient accuracy (less than 6.35 mm) was obtained.

3.4. Experiment procedure

The experiment procedure was as follows: At the beginning, the participants were asked to sign a consent form for participation in the experiment. They were then given an introduction (30 m) outlining the purpose of the experiment, the DURESS plant, the FBS framework, and the EID framework. Next, the participants had some limited time (5 m for each interface) to get themselves familiar with the FBS-DURESS and EID-DURESS interfaces. Calibration procedures followed, including positioning the participants, adjusting the camera, and calibrating the participants. During the calibrating, the participant first gazed at a sequence of dots and the participant's gaze point on the screen was predicted. Then the participant's position was adjusted so as to reduce the discrepancy between the actual position of the dots on the screen and the eyegaze point on the screen until a sufficient accuracy defined by the eyegaze equipment was obtained.

After calibration, the formal trials began. At the beginning, a participant was randomly assigned a specific treatment (e.g. FBS×L01); he/she viewed, supervised, and controlled the DURESS system for a period of time (last from 2 to 3 m up to 7–8 m). The participants were not told what scenarios (i.e. four scenarios: L01, L02, F01, F02) they were working with. If the participants felt that there was nothing wrong with the system, they were asked to control the system (including adjust the openings of the valves and the heaters) until reaching the dynamic equilibrium (the demanded temperature and flow rate of the water out of the reservoirs) as quickly as possible. Otherwise, they were required to diagnose the fault as quickly as possible. After each trial, the participants were required to conduct subjective evaluations including filling out a subjective rating form.

3.5. Data acquisition

For the purpose of the present study, the operator's hand movement was recorded. Specifically, a log file in the program was used to record (i) the operator's control action (i.e. mouse clicking), (ii) the time the action takes place, and (iii) the value of each state variable. The eye fixation data were collected by a built-in program with the eyegaze equipment as described before. In particular, the eyegaze points, their duration, and their coordinates were recorded in a real time manner and synchronously with the recording of hand movement through the log file.

As discussed before (see Figs. 5 and 6), the screen was divided into the regions corresponding to the state variable. Based on the data collected above, one can come up with the following information: (i) the total number of eye fixation and (ii) the total number of hand movement, for each region. It is noted that the total number of eye fixation is calculated by the total eye fixation percentage, which is defined as: the total number of eye fixation in a region over the total number of eye fixation over the entire interface region.

Table 1
Summary of the results of the comparison between EID-DURESS and FBS-DURESS

	FBS-DURESS	EID-DURESS	P^{**}	Better
Eye fixation (%)	90.8	95.8	<0.0001	FBS
Pupil diameter (mm)	3.189^{A*}	3.193^{A}	0.4988	
Completion time (s)	214.82^{B}	252.90^{A}	0.050	FBS
Detection time	112.05^{A}	110.117^{A}	0.8309	
Detection rate	103/120	86/120		FBS
Failure rate	30/480	57/480		FBS
RSME	57.188^{B}	62.229^{A}	<0.0001	FBS
Narrative	85%	15%		FBS

**Significance level $P<0.05$. *Means with different letters (comparison within each row) are significantly different (Duncan's multiple range test).

4. Results

4.1. General comparative results for the two interfaces (Lin et al., 2003)

The comparative experimental result reported in (Lin et al., 2003) basically says that the method to display the abstract function concept in the EID interface is not adequate. This method may increase the operator's mental workload but not improve the operator performance. The summative general result is further given in Table 1. In this table, the following measures, the eye fixation, the pupil diameter, RSME (subjective), and narrative (subjective), are supposed to give measurements on the operator mental workload.

4.2. Results related to the hand–eye measure

Only data for the normal control operation task are considered for the purpose of the present study. Furthermore, only data for one replicate are examined. Also, three typical participants were closely examined, and they are, respectively, participant #1 (poor performance); participant #16 (medium performance); and participant #20 (good performance). The performance grades (poor, medium, and good) were based on their performances on the normal control tasks (i.e. L01 and L02; see the previous discussion) done on the FBS-DURESS interface; in addition, their performance on FBS-DURESS is better than their corresponding performance on EID-DURESS, respectively.

Fig. 8 presents the frequency of hand movement and the frequency of eye movement for the different regions on the interface display for these three participants and the two interfaces, respectively. The selected regions (R-VOL1, H1, PVB, and H2) of eye fixation and mouse clicking behaviors were examined; specifically the difference in frequency between eye fixation and mouse clicking was examined. The *t*-test statistically shows that these two frequencies have a significant difference ($P<0.05$).

Table 2 shows the following pieces of information (for EID-DURESS): (1) the ratio of the eye fixation over the mouse click, (2) the ratio of the eye fixation over the operation time, and (3) the ratio of the mouse click over the operation time. The eye fixation and mouse click are calculated, respectively, by summing up their frequencies on all

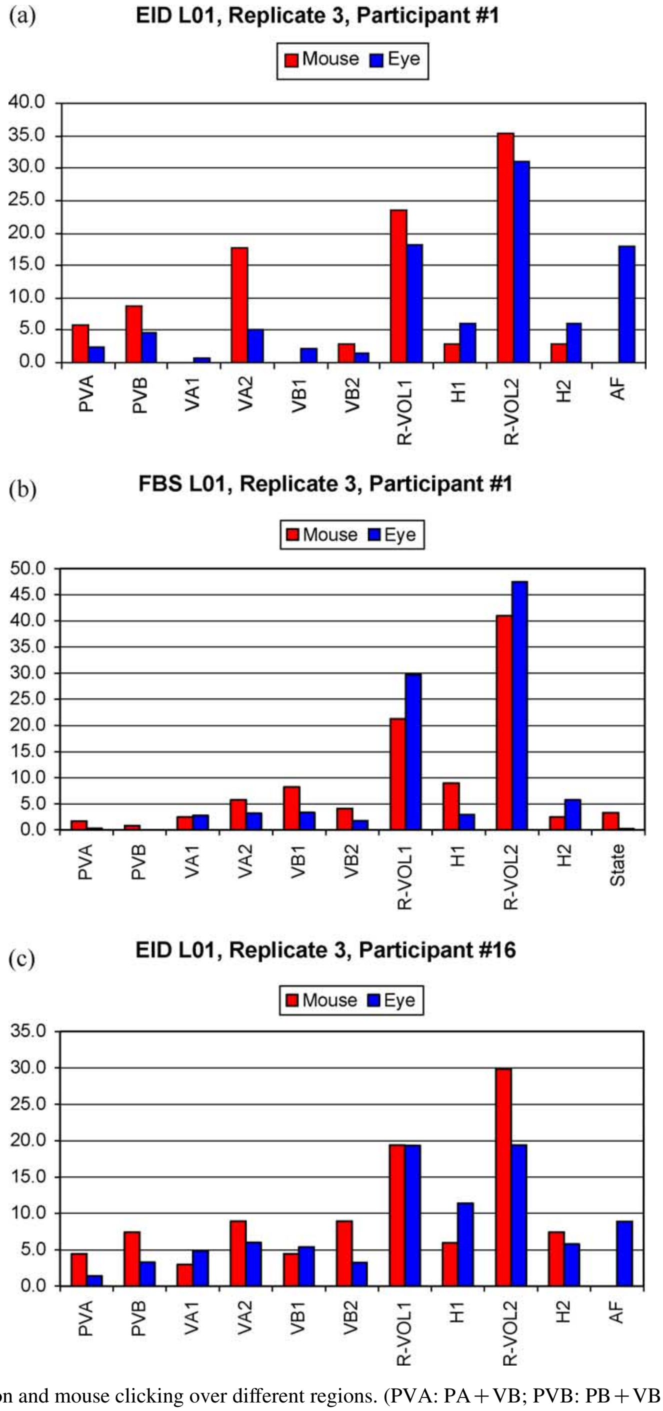
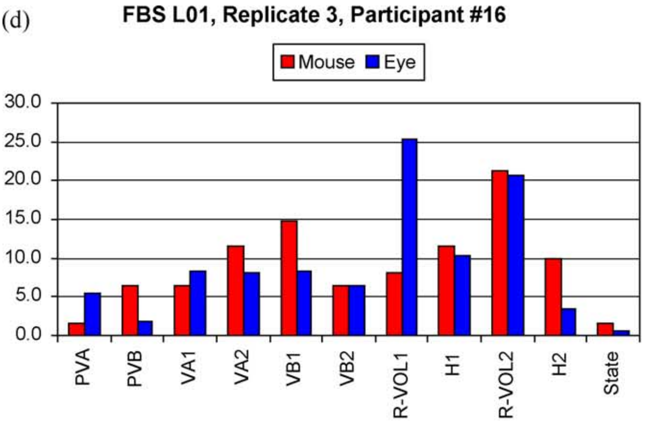
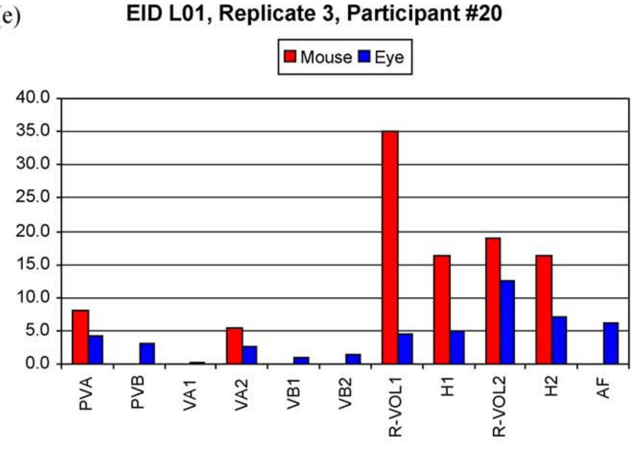


Fig. 8. Eye fixation and mouse clicking over different regions. (PVA: PA + VB; PVB: PB + VB; R-VOL1: R1 + VO1; R-VOL2: R2 + VO2; AF: abstract function of the EID; State: state diagram of the FBS).

(d)



(e)



(f)

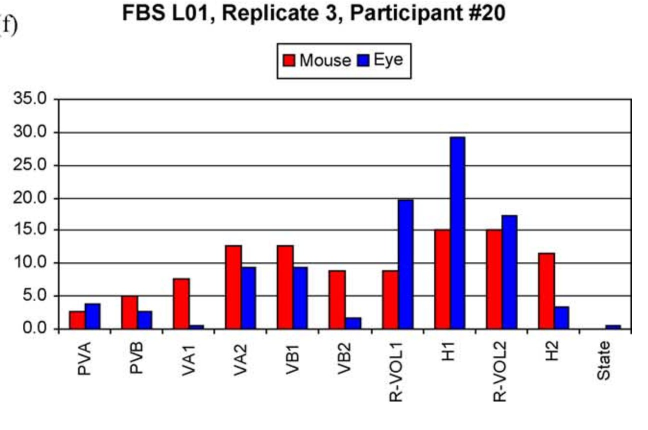


Fig. 8 (*continued*)

Table 2
The overall eye fixation, mouse clicking, and their ratio for EID-DURESS

Participant	Eye fixation/mouse click	Eye fixation/time	Mouse click/time
#1	4.63	2.96	0.64
#16	4.80	2.69	0.56
#20	5.20	2.34	0.45

the variables in Fig. 8. It is also noted that for each participant, his or her completion time is different. Therefore in the information items (2) and (3) (in Table 2), the division of the operation time is made.

5. Discussions

The result that the hand movement and eye movement behaviors have significant difference should positively test Hypothesis (i); that is to say, the joint consideration of these two behaviors is meaningful in understanding effectiveness of a cognitive action or process.

From the result shown in Fig. 8, we can see a pattern in the regions 7 and 8 (R-VOL1 and R-VOL2), that the number of the eye movement is greater than that of the hand movement in FBS-DURESS, whereas in EID-DURESS the situation is in opposite. This could be explained such that the operation performance in EID-DURESS is less efficient; there must be some hand movements (i.e. actions) in EID-DURESS are more than necessary. It is also noticed that the regions 7 and 8 contain two major controls in the plant, namely VOL1 and VOL2, which means that the hand movement in these two regions, respectively, must be more active than in other regions. In EID-DURESS, nearby these two regions are two abstract function regions, namely regions 10 and 12, respectively, which may have taken some attention away from the operators yet have not given useful cues to performance improvement. These findings are in agreement with our previous experimental result given in Table 1, and they should imply a positive test for Hypothesis (iii).

From Table 2, in particular the third and fourth columns, we can see the pattern or trend that the good operators use less eye fixation and mouse click in both. It is noted that the information of less eye fixation and less mouse clicking does not infer any inter-relationship between the eye fixation and the mouse clicking. The second column in Table 2, however, has provided enhancement to the knowledge obtained from the eye fixation and mouse clicking, respectively; that is, the higher ratio (eye fixation/mouse clicking) implies the more experienced operator. The finding here should imply a positive test to Hypothesis (ii).

6. Conclusion and future work

The study presented in this paper has attempted to postulate a notion called effective attention allocation and further to propose a measure which combines eye fixation and mouse clicking for this notion. At present, our study is restricted to whether this new measure is sensible qualitatively. From the experimental study, it can be concluded that the inter-relationships between the eye fixation and the mouse clicking, such as the eye fixation over the mouse clicking ratio and the differentiation between the eye fixation and the mouse clicking frequencies, are sensitive to operator's performance variations on different interfaces and different operators.

There are several limitations of the present study, which require further work. *First*, the analysis of the result presented in this paper has not followed the statistics method; instead we only picked up several representative participants. *Second,* we have not done a more detailed time domain analysis about the inter-relationship between the mouse clicking and the eye fixation.

Future work has the following considerations. *First*, we need to get time-domain information, i.e., the dynamics of the actions (eye and hand). *Second*, we pick up any eye fixation at time t, and we determine the allowable action and the optimal action domains for time t and that particular scenario. *Finally*, by examining what is the actual action an operator does, we can peer into whether the cognitive process, which is represented by eye movement behavior, is an effective one for that particular scenario and at that particular point of time *t*.

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