Evaluating usability of the Halden Reactor Large Screen Display: Is the Information Rich Design concept suitable for real-world installations?

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Abstract: Large Screen Displays (LSDs) are beginning to supplement desktop displays in modern control rooms, having the potential to display the big picture of complex processes. Information Rich Design (IRD) is a LSD concept used in many real-life installations in the petroleum domain, and more recently in nuclear research applications. The objectives of IRD are to provide the big picture, avoiding keyhole related problems while supporting fast visual perception of larger data sets. Two LSDs based on the IRD concept have been developed for large-scale nuclear simulators for research purposes; they have however suffered from unsatisfying user experience. The new Halden Reactor LSD, used to monitor a nuclear research reactor, was designed according to recent proposed Design Principles compiled in this paper to mitigate previously experienced problems. This paper evaluates the usability of the Halden Reactor LSD, comparing usability data with the replaced analogue panel, and data for an older IRD large screen display. The results suggest that the IRD concept is suitable for use in real-life applications from a user experience point of view, and that the recently proposed Design Principles have had a positive effect on usability.
Keywords: Large Screen Display; Information Rich Design

1 Introduction

This paper first presents two challenges: i) challenges in cognition of large data sets, and ii) the fragmented keyhole view of complex processes. Next it describes how Large Screen Display (LSD) design can help maintain the greater picture of large-scale processes, followed by this papers' research questions. The objectives of Information Rich Design (IRD), the Design Principles used, and a description of the Halden Reactor LSD are presented. Followed by the usability evaluation method, results and discussion. Lastly, topics for further work are outlined.

1.1 Large data sets & keyhole effects

In the aftermath of the Three Mile Island and Chernobyl disasters, there has been an increased focus on control rooms' user interfaces, and how large data sets with thousands of variables and control loops challenge human capacity. Endsley [1] described how *"current technologies have left human operators extremely challenged in this process"*.

In addition to the great complexity of large data sets, there are challenges associated with applying new technology, as analogue hardwired panels are replaced with flexible low-cost desktop displays. Vicente, Roth & Mumaw [2], and Salo, Laarni & Savioja [3] pointed to possible keyhole effects, and highlighted how it can be more difficult to obtain an immediate overview of the process situation on smaller desktop displays than on larger panels. This unfortunate fragmented view is often referred to as the keyhole effect; see Woods [4].

One possible solution to such challenges is to use LSD technology to display the big picture, supplementing desktop displays. Andrews *et al.* [5] suggested however that it is not sufficient to up-scale pictures intended for smaller desktop displays. This is also in line with Endert *et al.* [6], who found that the choice of visual encodings in Large Displays directly affected users' performance.

The U.S. Nuclear Regulatory Commission's well-known guidelines for the nuclear domain, NUREG-0700 [7], provide some objectives for overview displays (of which LSDs are one of several possible formats): "*An overview display should provide a characterization of the situation as a whole in a concise form that can be recognized at a glance*",

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suggesting that graphics and layout must be taken into consideration for visualization of such large data sets.

In sum, this suggests that LSDs should be designed for this purpose from the ground-up to allow for fast visual perception, and to avoid keyhole effects.

1.2 Research questions

Skjerve and Bye [8] described how the Norwegian Institute for Energy Technology (IFE) in Halden has performed research activities on display concepts for nuclear and other complex environments over many years; one of its outcomes is the IRD concept.

IRD has previously been applied in LSDs for commercial use in the petroleum domain, and more recently in two research applications for large-scale nuclear simulators (1st and 2nd generation displays). It is however necessary to evaluate whether the newly developed IRD Halden Reactor LSD has improved on the previously unsatisfying user experience with the 1st and 2nd generation LSDs. For this reason, this paper explores the following two research questions:

- Is usability of the IRD concept satisfying for real-life industrial installations?
- Have the recently proposed IRD Design Principles improved perceived usability of the LSD concept?

The IRD concept is not domain specific, and for this reason, the first research question is asked broadly, not specifically for nuclear. The second research question is explored through the Halden Reactor LSD designed accordingly to modifications reflected in recent proposed Design Principles (compiled in this paper).

1.3 Earlier work on IRD

This paper extends on earlier work, which discussed the need for a design concept that supports fast visual perception [9]. More recent publications focused on realizing the concept on nuclear LSDs; a 1st generation LSD in Finland [10]; and a 2nd generation LSD in the Halden Man-Machine Laboratory (HAMMLAB) Boiling Water Reactor Simulator (HAMBO) [11]. Two user tests have been done for the nuclear domain; see Laarni *et al.* [12, 13]. Theoretical foundation and design principles are recently published [13, 14].

2 Information Rich Design

2.1 IRD design objective

The objective of IRD is to present the big picture of the complex information space in-line with human cognitive capacity. For this reason graphical elements and their layout are designed to simplify larger data sets through Gestalt principles such as alignment and grouping.

This is illustrated in the left side of Fig. 1, where three process variables are visualized through horizontally aligned IRD generic mini-trends, using part-wise mathematical normalization of the measuring scale, the right side is not normalized (traditional approach). This generic qualitative indicator is used to visualize process data such as liquid level, pressure, temperature, and flow. The green arrow represents the target value (set point), while darker areas indicate high and low alarm limits.

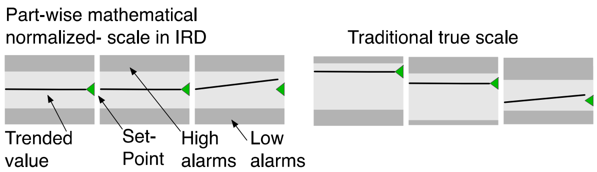

Fig. 1 IRD mini-trends on left side, a traditional true scale on the right side.

The IRD concept has also used animation effects to draw attention to new unacknowledged alarms, creating strong visual pop-out effects on key alarms; see Fig. 2.

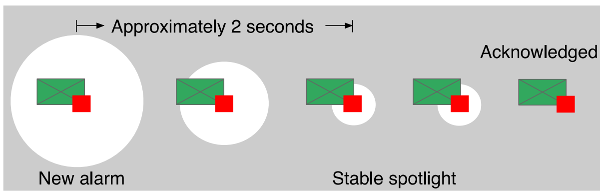

Fig. 2 Pop-out effect: incoming unacknowledged alarm visualized through dynamic alarm spot on green open valve.

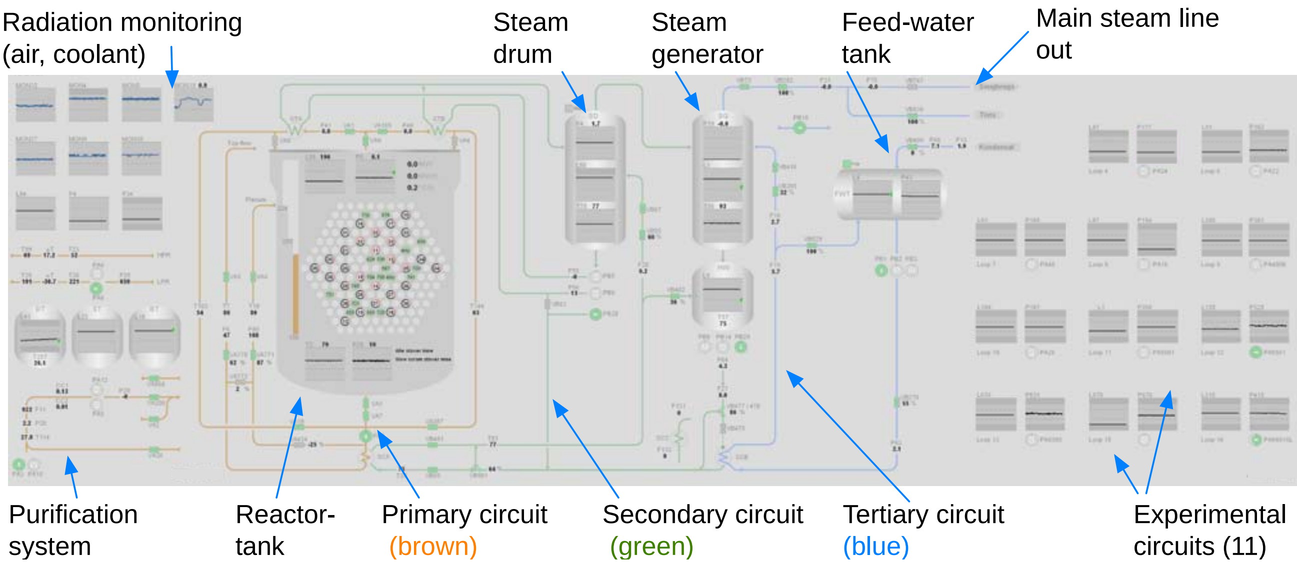

Fig. 3 The Halden Reactor LSD (4.5**m** x 1.4**m**) installed in the research reactor control room, main functionality.

2.2 Functionality of the Halden Reactor Display

The main functionality of the Halden Reactor LSD is illustrated in Fig. 3. It is designed to be complimentary to control room operators' desktop workstations, where the big picture is visualized on the LSD, while in-depth details and process interaction are reserved for desktop displays.

The LSD is designed to support process operators in a wide range of operational activities:

- Understanding the reactor circuits and the experimental loops.
- Supporting normal and safety-critical operation of the plant.
- Running the process up and down.
- Early detection of disturbances and abnormalities.
- Detection of unacknowledged alarms and key alarms.

2.3 Proposed IRD design principles

The IRD concept builds on well-established scientific theory on information visualization and human cognition. Findings from user tests and commercial IRD applications have been used to improve the concept iteratively during the last ten years.

The following principles (1) – (8) are compiled from two recent publications [13, 14], key references are included. The Halden Reactor LSD is designed according to these principles (1) - (8).

Display Graphics (1) – (3):

(1) Gibson [15] inspired the use of ecological psychology as a theoretical foundation for fast visual "pick-up" of data. How display graphics should be rich in *perceived affordances*, visualizing *substances*, *mediums*, *surfaces*, as well as their *constraints*. Tufte [16] explained how to focus on high data-ink ratio and dynamic data.

(2) Burns & Hajdukiewicz [17], and Tharanathan [18] suggested to use qualitative direct perception indicators to display data. We have however found trended indicators best in displaying plants´ dynamic response. Endsley *et al.* [19] inspired us to integrate target values, rate-of-change cues, and to visualize automation to keep operators in the loop.

(3) Ware [20] and Healey & Enns [21] explained how data should be given lower level pop-out effects through a visual feature hierarchy, providing cognitive support through rapid eye movements, achieved through graphics orientation, colour, size, and motion. We have found equally sized filled objects better than frames for alarm visualization and how to integrate alarm information within a natural context of graphical objects. Ware [20] described how a gentle animation is a preferred alternative to protrusive flashing or blinking in displays; we have used this to highlight new alarms.

Display Colours (4) – (5):

(4) Van Laar [22] described colour layering for displays. We have found that grey-scale has given readability problems in well-lit rooms using front-projected technology.

(5) Bullemer *et al.* [23] suggested a grey background colour in process displays, considering situation awareness, alertness, eyestrain and fatigue.

Display layout (6) – (8):

(6) Lidwell, Holden and Butler [24] described how Gestalt Principles reduce visual complexity through alignment and grouping. Duncan & Humphreys [25] showed how to avoid masking problems by limiting the number of different display objects.

(7) Ware [20], Healey & Enns [21] described mechanisms supporting fast top-down visual search in displays. Suitable means are lines, multi-scaled structuring elements, grouping, and open space, see Horn of & Halverson [26].

(8) Norman [27] inspired the use of a flat, externalized display layout (externalized visible elements).

2.4 Applying design principles (1) – (8) on the Halden Reactor LSD, Fig 3

In the following, numbers (1), (2), *etc.* refer to the applied principle from the previous section.

The main difference from the earlier 1st and 2nd generation LSD designs is a stronger focus on supporting fast top-down visual search, and to display the plant's dynamic response through trended data representation.

For improved top-down search, open space is used (7), including familiar large- and small-scaled physical structures (7) as *substances* (1) and grey backgrounds (5) for dynamic data. Major flow-lines (7) are used to visualize fluid *medium* (1) connecting process objects. The display uses no display hierarchy (8).

Visual simplicity (6) is achieved by alignment and grouping of variables. Dynamic process response is displayed through generic indicators (2) with trended *surfaces* (1) and its *constraints* (1) (alarm limits). Graphical symbols focus on dynamic data, *perceived affordances* (1). Key alarms are shown as filled objects and animation (3) as strong pop-outs on the top level of a visual colour layering hierarchy (4).

2.5 Removing the panel, implementing the LSD

The design process started in 2007, and the graphical design was developed through 14 iterations by a design team including the author (designer), expert operators, and a computer expert (implementing the graphical design). A prototype was installed on two 30" displays early in 2012, followed by correction of major flaws prior to final installation in the spring of 2012. The design team met regularly during the first months after the installation to further correct errors.

Figure 4 shows the dismantling and removal of the analogue Panels. IFE engineering, electro and maintenance competence were used in planning this process, which was challenging while running the research reactor. Disconnecting and reconnecting were done according to scheduled reactor stops.

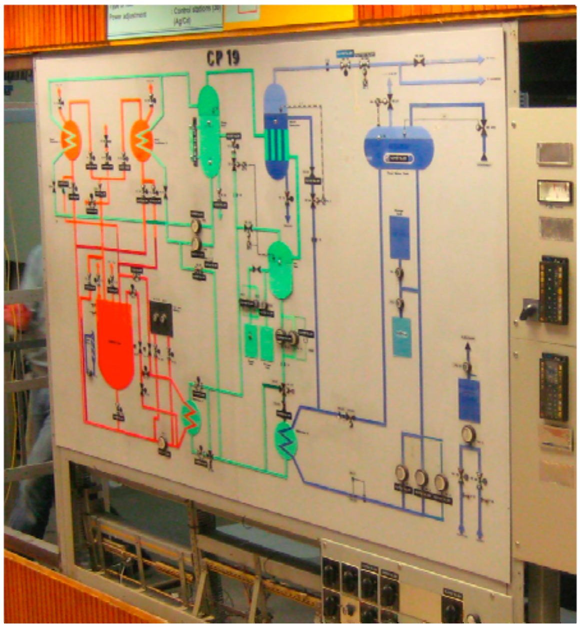

Fig. 4 The Panel (CP 19) is dismantled, preparing for the new Halden Reactor LSD.

Figure 5 shows a part of the new LSD from the control room operator's normal seated position.

Fig. 5 The Halden Reactor LSD.

A black frame surrounding the LSD was installed to enhance contrast. The LSD is displayed on a StarGlas 60 matte glass screen mounted in an aluminium frame with dimensions 4.5**m** x 1.4**m**. A new ceiling with adjustable lighting was installed during the process.

3 Method

This paper's evaluation of the IRD concept compares: i) the Halden Reactor LSD, Fig. 3 & 5, ii) the replaced analogue Panel, Fig. 4, iii) the earlier 2nd generation HAMBO LSD, Fig. 6.

The usability data reported in this paper for both LSDs and the replaced Panel is based on the System Usability Scale (SUS) [28] questionnaire data. Additional data for operators' subjective perceived support is collected for the Halden Reactor LSD and the replaced Panel.

3.1 Two questionnaires

The SUS used in this paper was developed as part of the usability-engineering programme at Digital Equipment Co. Ltd., Reading, UK, and has been made freely available for evaluations in usability assessment [28]. Ten items are rated on a five-point scale. Ratings are then calculated into a final usability score (0-100).

A questionnaire addressing the operators' subjective opinion of perceived support was also used for the Halden Reactor LSD and the replaced Panels. Five items were scored (0-7): detecting alarms, detecting disturbances, perform process actions, obtain a shared awareness, and perform tasks without high mental workload.

3.2 SUS scores as percentile rank

SUS has become an industry standard with references in over 600 publications. Sauro [29] has reviewed existing research on SUS and analysed data from over 5000 users across 500 different evaluations. The average SUS score from all 500 studies is 68 (0-100).

Sauro suggests interpreting the SUS score by transforming this to a percentile rank. For example, a SUS score of a 74 converts to a percentile rank of 70%, meaning that the system tested has a higher perceived usability than 70% of all products tested. Similarly a score above 80.3 represents the top 10% of scores.

3.3 SUS reliability and validity

Reliability refers to how consistently users respond to the items (the repeatability of the responses). The SUS has been shown to be reliable and to detect differences at smaller sample sizes than other commercially available questionnaires [29]. SUS has also shown to effectively distinguish between

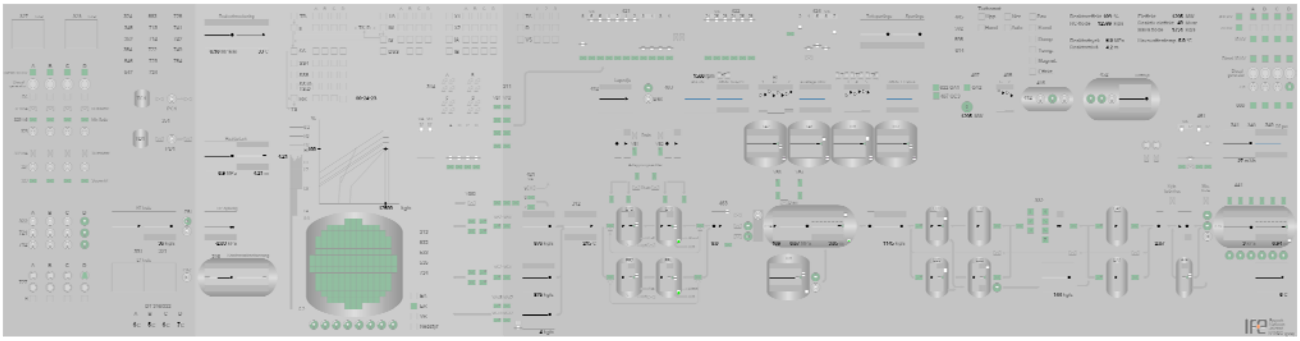

Fig. 6 The 2nd generation HAMBO LSD, installed on nuclear simulator in Halden, 6**m** x 1.5 **m**.

unusable and usable systems as well as or better than proprietary questionnaires; correlating highly with other questionnaire-based measurements of usability [29]. This suggests that SUS results have sufficient validity in measuring perceived usability.

3.4 Evaluation of the Halden Reactor LSD

All crews working at the Halden Reactor participated in this study, except persons involved in designing the Halden Reactor LSD, with a total of 22 operators. Two researchers at IFE interviewed the operators; neither had participated in designing the LSD. Both SUS scores and data from operators' subjective opinion of perceived support were collected. This was carried out in early autumn 2012, approximately 1-2 months after implementing the LSD. It was an objective to assess operators' early impressions of the LSD.

3.5 Evaluation of the replaced Panel

The evaluation of the replaced Panel was carried out simultaneously with the evaluation of the Halden Reactor LSD; the Panel was used to control the same process in the same control room as the Halden Reactor LSD. The same control room operators participated in this evaluation, using the same questionnaires.

At the time of data collection, the Panel was dismantled and not in use. However, operators were interviewed in an environment with the Panel present.

3.6 Evaluation of the 2nd gen. HAMBO LSD

The evaluation of the 2nd generation HAMBO LSD (Fig. 6) was done in an earlier usability study performed in a laboratory (HAMMLAB) on a large-scale nuclear simulator (HAMBO) in 2011. Seven crews from different Nordic nuclear plants participated, in total 20 operators; see Kaarstad and Strand [30] for a full description of this study.

The participants were interviewed and responded to the same SUS questionnaires as for the Halden Reactor LSD and Panels, after running through a set of scenarios. Data were however not collected for operators' subjective opinion of perceived support.

3.7 Limitations

We recognize that there are weaknesses and limitations in this paper´s usability data comparison. Most notably, the SUS score for the recent study (Halden Reactor LSD + Panels) and older study (2nd generation HAMBO LSD) are not directly comparable. The data were collected in different conditions, from different nuclear processes and by different participants.

The Halden Reactor Display and Panels are evaluated in a real life operative control room, after 1-2 months of use, while the older 2nd generation HAMBO LSD was evaluated in a simulator setting, with only a limited (one day) familiarization. The replaced Panels were however obsolete and taken out of operation at time of evaluation.

In addition, we emphasize that SUS is not designed for testing LSDs in particular, but for system usability in general. In sum, this suggests to use SUS scores only as indications, and not as directly comparable data.

4 Results

Individual SUS scores are presented, (Fig. 7), and then the total calculated SUS score is converted to a percentile rank, (Fig 8). The perceived support questionnaire results are presented at the end, (Fig. 9).

4.1 Individual and percentile SUS scores

Figure 7 shows the individual SUS scores of the Halden Reactor Display (total 83), the replaced Panels (total 77) and the HAMBO LSD (total 59). Figure 8 shows the percentile rank (%) for the Halden Reactor LSD (95 %) red line, representing a top 5% score. The replaced Panels (77 %) blue line, and the HAMBO LSD (30 %) green line.

4.2 Operators subjective perception of support

Figure 9 shows the perceived degree of support, comparing the Halden Reactor LSD with the replaced Panel. These data were not included in the study of the HAMBO LSD.

The operators rated the Halden Reactor LSD significantly better on perceived support than the Panels with respect to alarm detection [$F(1,38)=206,13$, $p=.000$)]; disturbance detection [$F(1,38)=229,23$, $p=.000$)]; performing process actions [F(1,38)=64,80, p=.000)]; shared awareness [F(1,38)=21,87, p=.000)] and workload reduction [F(1,38)=16,10, p=.000)].

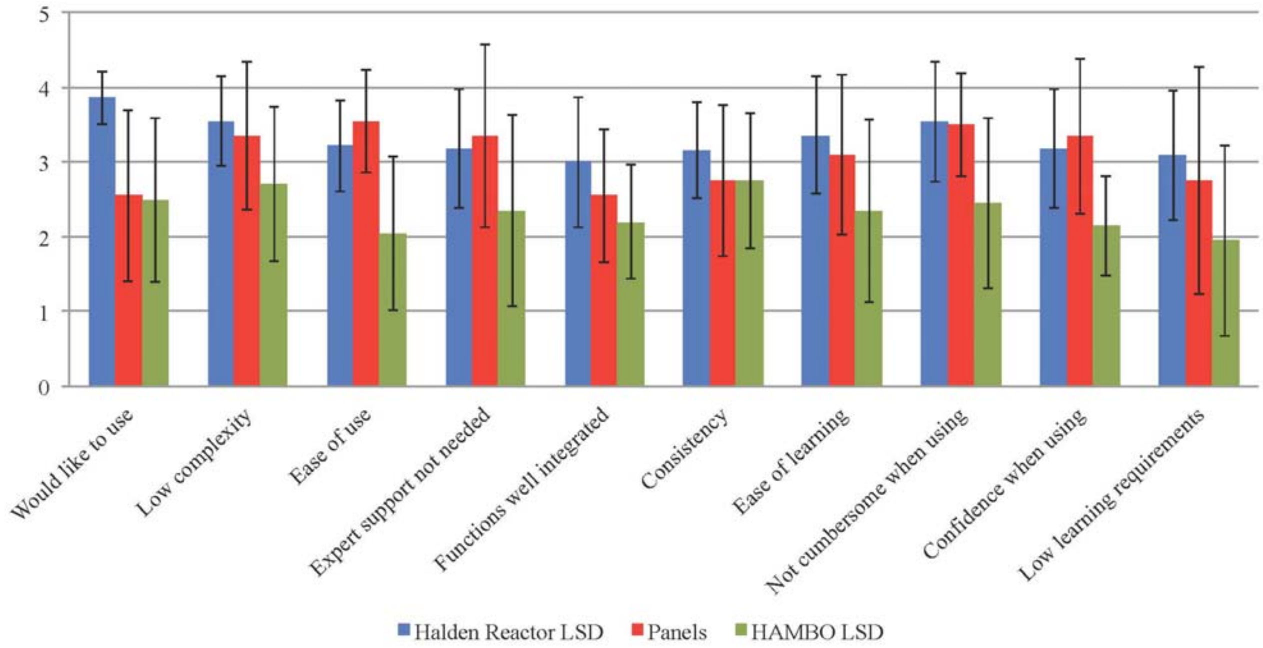

Fig 7 Individual SUS scores. (1: Strongly disagree; 5: Strongly agree)

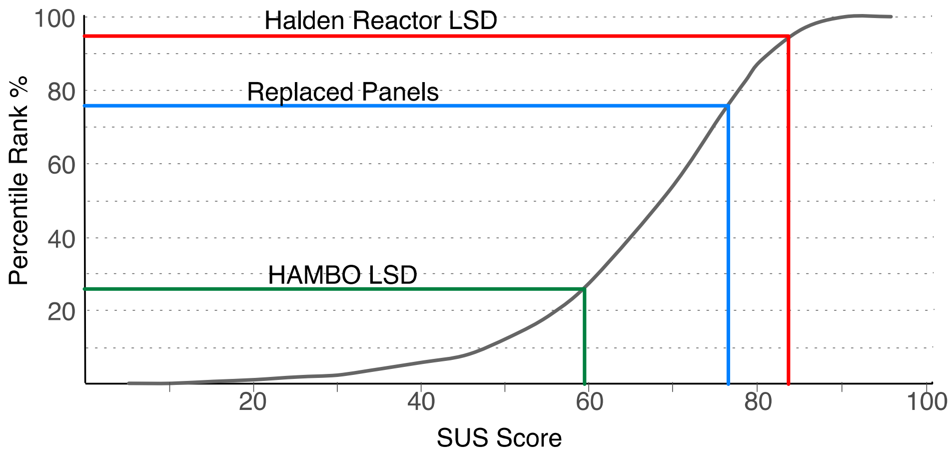

Fig. 8 SUS scores converted to percentile rank, based on Sauro [29].

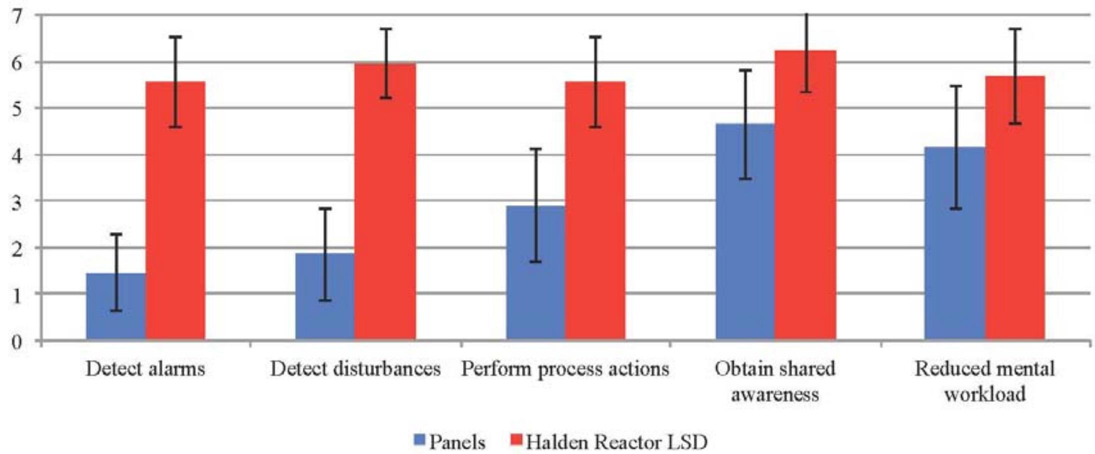

Fig. 9 Perceived support. (1: Low degree, 7: High degree)

5 Discussion

The first research question - *Is usability of the IRD concept satisfying for real-life industrial installations?* - Is discussed by looking at System Usability Scale (SUS) data and the perceived support for the new Halden Reactor Display and Panel. In addition we look at historical SUS data (percentile rank).

For the second research question - *Have the recently proposed IRD Design Principles improved perceived usability of the LSD concept?* - We draw comparisons between SUS data for the new Halden Reactor LSD and the earlier 2nd generation HAMBO LSD.

5.1 Is usability satisfying?

The SUS data (Fig. 8) indicates that the Halden Reactor LSD has a high level of user satisfaction, being among the top 5% of SUS scores. By comparison, the replaced Panels have also a high score, being among the 25% highest SUS scores. From the individual SUS data (Fig 7), we can see particularly that the item "would like to use" seems to be quite high for the Halden Reactor LSD.

The operators' ratings of perceived support (Fig. 9) in different tasks have no particularly low rating for the Halden Reactor LSD, with a higher score than the old Panels for each task. The biggest difference is found in detection of disturbances and alarms. This indication seems to be in accordance with the general design objective of IRD: helping operators to spot deviations at a glance. The item "shared awareness" obtained the smallest difference in perceived support between the Halden Reactor LSD and Panels. This suggests that older Panels are also suited to facilitate a shared awareness, which is in line with work by others, *e.g.* Vicente *et al.* [1] and Salo *et al.* [2].

The data analysed so far, suggests that the IRD Design Principles as used in designing the Halden Reactor LSD has become more mature and suitable for use in real-life nuclear processes from a user experience point of view. It should also be noted that the Halden Reactor LSD is actually being used in a "real-life" operational control room, which strengthens these findings. We stress however that the current data is not representing operator performance, only usability.

5.2 Have the Design Principles improved perceived usability?

The overall SUS score for the 2nd generation HAMBO LSD was 59 in the former study, and 83 for the new Halden Reactor LSD in the current study (Fig. 8). These numbers are however not directly comparable, as data was collected from two different user groups in two different operational contexts. However, the same scale was used for evaluating usability, and the results indicate a significant increase in usability for the Halden Reactor LSD. One reason for this result can be a stronger focus on a more familiar "mimic" display type layout, focusing on top-down visual search, as outlined in this paper´s Design Principles, displaying coloured lines and familiar background shapes.

We are however cautious to draw definitive conclusions on our second research question, since the two displays were tested under different conditions. The results are however in general promising, suggesting that the recent proposed design principles should be kept.

5.3 Reflections & Further work

Though the usability results in this paper are promising for the Halden Reactor LSD, both real performance data, and display technology should be further studied.

As a first step, in-depth discussions with control room operators using the Halden Reactor LSD would be beneficial in finding out what works well and what should be further improved. Performance data for the IRD concept would also be beneficial, particularly measuring Situation Awareness levels, comparing IRD to other display concepts to see if the design concept really increases Situation Awareness levels in complex scenarios.

The concept of part-wise mathematical normalization of the measuring scale as used in IRD introduces non-physical visualization of process variable behaviour (Fig. 1). This can however result in operators building errant mental models of processes, as described by Endsley *et al.* [19]. The effect of this should be further studied.

We suspect further that the choice of display technology affects the usability results. The 2nd generation HAMBO LSD used front mounted video projectors, while the Halden Reactor LSD represents an advance in rear-projection technology, increasing the contrast ratio considerably, which might have positively influenced the SUS score.

We have designed LSDs using other technologies, such as high-resolution display cubes in some commercial applications for the petroleum domain; see eyevis technology [31]. Even if this type of technology introduces unfortunate visible frames, which appear as thin lines in the LSD, it further increases the contrast ratio, and the picture is much brighter than the rear projection technology used in the Halden Reactor LSD. Such technology appears to us as an advantage, particularly on grey-scale colour layering LSDs, suggesting that this technology should be investigated also for use in the nuclear domain.

Technology is however evolving rapidly, and there is much to explore in emerging display technologies. Touch technology is particularly interesting. Can operators interact directly with the process through touch technology on larger high-definition surfaces? What opportunities exist for the use of haptic feedback from the display surface?

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