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Perceived usefulness and usability of overview displays in nuclear control rooms

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Overview displays are becoming more common in the nuclear industry, both in digital and hybrid main control rooms. Even though overview displays have been present in the industry for several years, there is still a lack of empirical data on overview displays' implementations, its usefulness, usability and even performance impact for the operating crews. This paper explores whether usability ratings predict perceived usefulness in overview displays. We study connections between overview displays' usability, its reported use, and perceived usefulness and support. This is done through three studies in different control room settings, with different versions of overview displays: a) in a real-world control room with six crews of two operators each in a research reactor main control room, who had long-term experience with an overview display; and b) in a research simulator environment with two crews of four licensed operators each, who experienced complex full-scale scenarios for a week, each crew using a specific overview display version. The operators were overall positive about the overview displays, and the results suggests that usability is a relevant predictor of perceived support. Limitations of the presented studies are also highlighted. Notably, all evaluated displays had a high usability score, thus constraining the variety of the ratings and compromising hypothesis testing in the current samples.

Keywords: Overview displays, control room, nuclear industry, usability, interface design.

1. Introduction

There is a trend in the nuclear industry to include digital interfaces in both new control rooms and as part of modernization projects. This often encompasses the adoption of overview displays (ODs). These are displays specifically designed to give operators either a plant overview or information about specific systems or tasks. The aim with these displays is to improve human performance by promoting situation awareness, team communication, and alleviating high workload situations. Braseth and Øristland (2013); Spielman et al. (2017). Figure 1 shows an example of a concept of a large human-scaled OD as targeted in the current work.

ODs are often presented as a mitigator of less awareness in digital control rooms when compared to analogue traditional panels where all information was clearly visible to the whole crew. Vicente, Roth, and Mumaw (2001).

Fig. 1. Illustration of a large screen overview display

Nonetheless, there is little evidence on the ODs' performance impact, and on the operators' evaluations and perceptions of the ODs after using them in realistic scenarios.

Gathering relevant data and making meaningful comparisons is further complicated by the fact that there is a large variety in type, size, design, and intended role of overview displays at different power plants. All these factors are very likely to mediate performance effects of the ODs and it is crucial to disentangle this relationship to inform and validate future efforts to develop and implement such displays.

1.1. *Overview Displays in Nuclear Power Plants*

Modernization and digitalization in nuclear industry has been slow and conservative due to safety concerns. Nonetheless, there is a clear need for integration of novel and digital technologies to support operators and replace old legacy systems that become obsolete or inadequate. Kovesdi, Joe, and Boring (2019). Potential advantages of well-designed digital control rooms for human performance are also described in literature. Boring et al. (2019).

A reported issue when replacing legacy analogue panels with individual computer and desktop-based workstations is an associated decrease in team and shared awareness. Vicente, Roth, and Mumaw (2001). When using the older analogue panels, it is easier to see what each team member is working on, supporting team awareness in an intuitive way. This advantage can be lost when using individual workstations and digital interfaces. To circumvent this and provide operators with common ground and increase shared and team awareness, ODs are introduced in control rooms.

ODs are usually intended to be accessible and usable by multiple team members simultaneously, provide information about the general plant status and are oftentimes relatively large. NUREG-0700 (Rev. 3, O'Hara & Fleger 2020) states that an OD *"[...] should provide an overview display if the display supports user performance by combining and integrating diverse plant data in a way that informs personnel of important conditions and allows them to see the overall status of the plant or process*". O'Hara & Fleger (2020, p. 6-4).

Although past work on ODs in the publicly available scientific literature is rather limited, some aspects of this technology in nuclear main control rooms have been explored. Proposals for design of such displays have been brought forward such as in dos Santos, Teixeira, Ferraz, & Carvalho (2008); Braseth & Øristland (2013); Jokstad & Boring (2015); McDonald & Braseth, (2019), stressing the positive influence the overview displays are intended to have on team and situation awareness and performance by providing contextual and relevant information to operators in specific scenarios. However, there is a strong need for additional data about: performance effects of ODs in general and of specific implementations; mapping of properties and concept of operations for ODs that could mediate the effects; operators' evaluation and usage of overview displays; and well as other stakeholders' opinions and motives.

1.2. *Role of Usability and Perceived Usefulness in Human Performance*

This section explores the concepts of usability and perceived usefulness in the context of ODs, starting by describing the two concepts and discussing their links to human performance.

One of the most influential models in the conceptualization of new technology and user adoption is the Technology Acceptance Model (TAM, Davis and Venkatesh, 1996), see figure 2. It explains how external variables affect perceived usefulness and perceived ease of use (which can be interpreted as "usability"). In turn, these aspects will influence behavioral intention which impacts actual use of the system. In the model, there is an expected influence of perceived ease of use on the perceived usefulness. This assumption is used as a motivation of the current work in this paper.

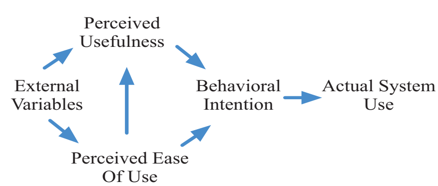

Fig. 2. TAM, Davis & Venkatesh (1996)

Usability is defined by the International Organization for Standardization as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" and is thus directly linked to human performance. Longo (2017). High usability generally means better performance, and self-report measures are often used in the literature to access it. Sonderegger & Sauer (2010); Reinecke & Bernstein (2011).

Perceived usefulness relates to performance expectations that users have when thinking about a specific technology or product. These are then to influence their intention to use the product, together with the perceived ease of use.

The influence of perceived usefulness on user and system performance has been found to be positive. From studies in other applications it was found, for instance, in healthcare settings that perceived usefulness had a direct positive effect on user performance. Chirchir, Aruasa, & Chebon (2019). Somewhat contrary findings were reported by Nugroho, Dewanti and Novitasari (2018), who could not find a significant effect of perceived usefulness on user performance in the implementation of an e-learning tool. The authors raise the concern that this might have been due to the mandatory nature of the implementation and could play out differently if the system would be adopted voluntarily. In e-learning, others have found a positive effect of perceived usefulness on performance, even though other factors like motivation were found to be more impactful. Saadé (2007).

1.3. *Present work and research question*

An analysis of the current industry practices reveals that there is high variation on the motivations to integrate overview displays, their design concepts, and their specific implementations. Bloch, Braseth, & McDonald, (2022). From this, it is difficult to assess and analyze ODs as an overarching design feature, since each specific implementation is intrinsically different. We argue that the discriminative impact of ODs on human performance is highly dependent on the specific characteristics of each display, including its design and operational implementation.

In this paper, our research question is: *Do usability ratings predict perceived usefulness in overview displays?* Through three studies, we explore this complex relationship by analyzing the connections between ODs usability, its reported use, and perceived usefulness.

2. Method

2.1. *Participants*

The operators in the studies came from different power plants. In total there were 20 participants (all male) including 12 in Study 1, four in Study 2 and four in Study 3. While operators in study 1 performed the study at their home plant, operators in study 2 and 3 had more restricted experience, as they performed the study in a research facility and used the OD for four days. In study 1 the participants had an average age of 46.9 years (*SD*= 8.2), in study 2 of 36.0 (*SD*= 4.3) and in study 3 of 33.8 (*SD*= 4.3).

2.2. *Measures*

A mixed-method approach was chosen including questionnaires and interviews. The standardized Systems Usability Scale (SUS, Brooke, 1995) – items are presented in Table 1. They are rated in a likert scale from 1 (strongly disagree) to 5 (strongly agree).

Table 1. Systems Usability Scale Items

1	I think that I would like to use this overview display frequently.
2	I found the overview display unnecessarily complex.
3	I thought the overview display was easy to use.
4	I think that I would need the support of a technical person to be able to use this overview display.
5	I found the various functions in this overview display were well integrated.
6	I thought there was too much inconsistency in this overview display.
7	I would imagine that most people would learn to use this overview display very quickly.
8	I found the overview display very cumbersome to use.
9	I felt very confident using the overview display.
10	I needed to learn a lot of things before I could get going with this overview display.

The authors also included a self-designed measurement presented in Eitrheim & Braseth, (2019) intended to capture concrete experience and perceived support from the OD in operational contexts. Its items are presented in Table 2. They explore specific aspects of perceived support in the scenarios that precede the surveys, rated on a scale from 1 (low support) to 5 (high support).

Table 2. Survey items on perceived support

	To what extent does the large screen display provide support to…
1	Detect alarms
2	Detect process disturbances
3	Make necessary process interventions
4	Achieve a good overall understanding of the process
5	Achieve a common situation understanding in the crew
6	form the basis for discussion and decisions in the crew

The interviews were conducted following a semi-structured interview guide focusing on both an overall assessment of the ODs, as well as exploring the experience and perceived usefulness of the OD in the scenarios. The interviews had a duration of 30 to 45 minutes.

2.3. *Interfaces*

2.3.1. Halden Boiling Water Reactor (HBWR)

The HBWR is a research reactor with a control room environment designed for two operators with support from a technical engineer. From their normal seated positions, they have visual access to analogue panels with traditional knobs, buttons, and smaller displays; personal digital workstations; and an OD with overview data.

Fig. 3. HBWR control room environment.

The OD is designed according to the Information Rich Design concept by Braseth & Øritsland, (2013), that proposes principles such as: 1) avoid keyhole and limited visual memory resources through a flat externalized layout, 2) make the display rich in perceived affordances, describing the plant state through many cues; 3) support rapid perception through qualitative trended indicators for pattern recognition; 4) efficient top down search awareness through grouping, open spaces and connecting lines, and 5) support bottom-up data-driven awareness, arranging graphics according to a visual hierarchy.

2.3.1. HAlden Man-Machine LABoratory (HAMMLAB)

HAMMLAB is a flexible research environment, where the conditions for a fully digital control room environment can be simulated. In the present studies, the room was arranged to support a crew of four operators, including a reactor operator (left) and a turbine operator (right) sitting closer to the large screen OD. A shift supervisor and shift technical assistant were sitting in the back of the room. Figure 4 illustrates the overall setup of the control room.

Fig. 4. HAMMLAB control room environment

The same simulator and workstation displays were used in study 2 and 3. However, an upgrade to the graphics of the OD was performed between the two studies. Figure 5 shows the OD in study 2.

Fig. 5. HAMMLAB display in study 2

Figure 6 illustrates the OD in study 3, with a grey background and optimized graphics that consisted in a re-organization and selection of the information in the OD. The OD was designed to reduce clutter and improve readability using principles from the Information Rich Design concept. One such feature is the use of qualitative rapid perception graphics. The safety related components (Safety Injection system, Residual Heat Removal/Low Head Injection system and the Safety Injection Accumulators) were moved to a separate OD. The group of pump indications was removed due to redundancy. The Normal and Emergency Cooling Water systems were also removed.

Fig. 6. HAMMLAB display in study 3

2.4. *Procedure*

Study 1 was conducted at the operators' home plant. The operators were highly familiarized with the OD, since they operate the plant daily recurring to it. The operators had performed four specific scenarios including both unexpected (malfunction) and planned tasks before answering the surveys. After responding to the surveys, the participants were interviewed in group about the perceived usefulness of the OD, both on the specific scenarios they had experienced and on their daily activities. Two researchers were present at the interview, one as main interviewer and another as note taker.

Study 2 and 3 were conducted at a full-scale simulator (HAMMLAB). The participants received one day of training in the simulator and interfaces and then took part in three days of intensive complex accident and emergency scenarios before they answered to the surveys. The operators were interviewed in group about their opinions, perceptions, and experience with the OD during the week. Two researchers were present at the interview, one as main interviewer and another as note taker.

The interviews were not recorded and the combined notes from the two researchers informed the summary presented in this work.

Before the start of the studies the operators were brief on the purpose and methods of the current studies and signed an informed consent form, highlighting the voluntariness of their participation and providing details on how the data was going to be processed and stored.

3. Results

In this section we describe the overall findings from each of the separate measures used across studies, as well as the hypothesis testing analysis, and a summary of the interview data.

3.1. Systems Usability Scale

The standardized SUS ratings were very high in the current studies. Figure 7 illustrates the average ratings in each study. The average ratings ranged from 84.2 (*SD*= 10.1) in study 1, to 97.5 (*SD*= 2.0) in study 3 study and study 2 showed a rating of 93.8 (*SD*= 7.8).

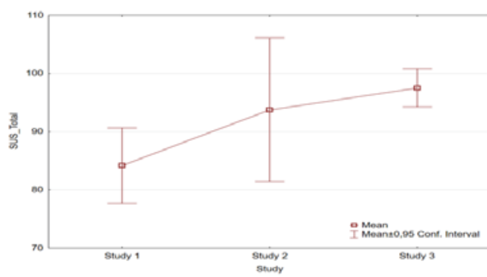

Fig. 7. Average SUS ratings

The SUS scale did not have a normal distribution (*Shapiro-Wilk test*= 0.88, *p*= .02). Subsequential testing through Kruskal-Wallis ANOVA showed that the SUS ratings was significantly different between the studies (*H (2, N=20)* = 7.4, *p*= .03). Post-hoc analysis showed that only the ratings between study 1 and study 3 study were significantly different (*U*= -2.39, *p*= .017), with higher usability in the HAMMBLAB B overview display.

3.2. Perceived Usefulness and Support

The pattern on the ratings for the usefulness/perceived support was equivalent to the SUS ratings with overall high scores. Figure 8 illustrates the specific ratings for perceived support from the OD in the experienced scenarios. It is possible to see that studies 2 and 3 had equivalent ratings, with averages above 4 in a scale with a maximum of 5 and the study 1 OD had slightly lower ratings. There ratings were not significantly different, as reported in the ANOVA: $F\ (2, 17)$= 1.96, p= .17.

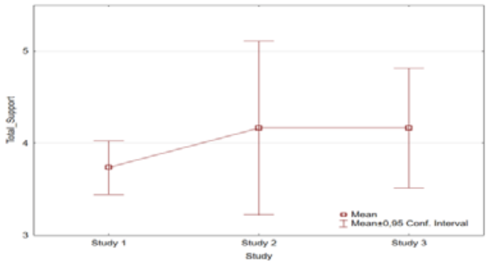

Fig. 8. Average ratings for perceived support

3.3. Hypothesis testing

We performed a regression analysis to test whether SUS ratings were able to predict the perceived usefulness /support ratings. The results revealed a significant effect: R^2= .42, $F\ (1,18)$ = 13.2, p= .002. This confirms our hypothesis that the usability of the OD (operationalized through SUS) would predict the perceived usefulness (operationalized as perceived support in the specific context of the tasks).

3.4. Debrief interviews

From the debriefing interviews, it was possible to find that the operators across all studies perceived the OD as a positive component in the control room interface. The operators in study 1, familiar with the use of the OD, mentioned that the OD is a very important tool – they have established work practices that involve the OD in daily operation and mention that removing the OD would imply a change in their routines. In study 3 the operators directly mentioned that the fact that they can see the OD from anywhere in the control room was reassuring to them. They reported feeling supported by the OD and considered it contributed to better performance by facilitating communication in the crew, allowing "at-a-glance" overview and monitoring of key parameters, and enabling them to quickly detect deviations.

The operators mentioned that the OD can be particularly useful in situations that are unexpected in contrast with planned tasks (study 2). In planned tasks the operators argued that the OD would not impact the awareness of the other crew members (study 2).

The presentation of information such as trends in the OD was particularly appreciated by the operators (study 2 and study 3) who mentioned that both trend charts and balance indicators facilitated the monitoring and the detection of deviations in the process.

The ODs were perceived as supporting situation awareness. In Study 3 the participants mentioned that it was good that the OD presented trends that allowed them to project into the future and easily detect deviations.

Teamwork was also referred as a factor that benefited from the OD inclusion (study 3). In study 2 the operators mentioned that they would need to "talk more" if the OD was not available as they could all easily see the important parameters at any point in the scenario.

The operators mentioned that adding or highlighting deviations in the OD would be good, for instance by including alerts and alarms (study 3). On the other hand, they also considered that the current amount on information was good and adding more could become confusing (study 2).

Summarizing, the interview data revealed that the tested ODs were mostly perceived as a positive aspect in the control room interfaces. The operators signaled advantages linked with better awareness on both the process and the crew members' activities, with communication and teamwork, and with management of workload in the scenarios. The operators did not refer to potential negative impacts of the inclusion of the ODs, but when prompted by the interviewer, they mentioned that dependence on the OD could be problematic if it is not available or malfunctions (study 1) and that if the amount of information in the OD is high it could be confusing for the crew (study 2 and 3).

4. Discussion

Our research question for this work was whether the usability ratings (operationalized through the SUS) would be able to predict usefulness (operationalized through perceived support ratings). Our results confirmed this hypothesis suggesting that OD usability is a relevant predictor of perceived support. We anticipate that this relation could be a relevant mediator on the performance impact of the ODs. As mentioned in the introduction, one of the big challenges identified for analyzing the impact of ODs is the fact that OD implementation in the nuclear industry can assume several forms: from size to positioning of the screens, but also attending to concepts of operation and represented systems, to the more design-specific components of graphical representation of elements and overall patterns and positioning in the display. Here, we argue that a contributor to the generalization of findings on the impact of ODs could be to aggregate the various implementation differences within the umbrella of the concepts of usability and perceived usefulness/support. Taking these factors as mediators might help the community to assess the impacts of OD on human performance across various deployments.

We found that the usability ratings were lower in the OD that was implemented in an operating control room. There are several factors that might contribute to this, from the specific implementation of the displays to the familiarization with the OD at the HBWR to the novelty effect of the ODs in HAMMLAB, as well as the overall consistency of the control interfaces, with a hybrid control room at the HBWR and a fully digital control room in HAMMLAB – all these factors should be explored in future work.

The interview data allowed us to better understand the meaning of the survey data and hypothesis testing. Moreover, it revealed that the operators were overall positive about the ODs in all studies. They listed mostly advantages of the OD and provided examples of situations where the OD was seen as facilitating the communication and even team performance.

In the three studies we registered very high scores in the SUS. If we take the reference value of 68 for the standardized ratings as shown in Lewis (2018), all the systems assessed here were clearly above that level with average ratings above 80. All of the ODs designs tested in these studies were created by the same institute. We see this as a disadvantage in the current study as there were clear similarities in the concepts, approach, and implementation of the ODs across the three studies. Only in one of the studies have we included participants working with a familiar OD – we believe that the familiarization with the OD might also be a relevant aspect to consider in the evaluations, since the novelty effect might hide more specific aspects on the use of the OD.

5. Conclusions and Future Work

In this paper we showed that usability ratings of ODs in a control room setting were able to predict usefulness ratings. The added findings from the debrief interviews confirm this, highlighting an overall positive assessment from the operators on all the presented ODs.

In the future we will further explore the links between usability, perceived usefulness, and human performance with more varied population samples, and broadening the type of ODs and their implementations, by collecting data with operators using the ODs at their home plants, where the novelty effect can be mitigated. Likewise, a relevant aspect to consider in future work is the inclusion of objective performance measures related to the specific scenarios or tasks that the operators execute. This will enable us to expand the knowledge and the hypothesis testing, linking usability, perceived usefulness, and performance.

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