Effects of Digitalization of Nuclear Power Plant Control Rooms on Human Reliability Analysis – a Review

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Abstract

The changes in the operating conditions of the main control room of nuclear power plants due to new digitalized human-system interfaces (HSIs) pose challenges to traditional human reliability analysis (HRA) methods. This paper reviews current knowledge about the effect of digital HSI on human behaviour and reliability, relevant performance shaping factor (PSF) taxonomies as well as research on the effect of PSFs on human error probability estimates in advanced control rooms (ACRs). It cannot be generally concluded that either analogue or digitalized control rooms would be always better than the other. ACRs have the potential to offer error reducing and supportive features to the user, but may also introduce increased complexity and interface management tasks as well as potentially error-prone team working practices. Some effects seem universal, but most depend on the specific design. The main PSF categories presented in HRA methods and international guidelines seem still relevant in ACRs. Quantitative empirical studies show that especially training and experience, availability and quality of procedures as well as task type or complexity are important factors. However, digitalization changes the way in which the PSFs should be defined and measured, and the effects of PSFs on the error estimates may be different.

Keywords

Human Reliability Analysis; Digitalization; Advanced Control Room; Nuclear Power Plant; Review; Performance Shaping Factor

1. Introduction

This paper reviews current knowledge about the effects of digitalization of nuclear power plant (NPP) main control rooms (MCR) on human reliability analysis (HRA). Through modernisations and new-builds, MCRs with modern digital human-system interfaces (HSIs), so called advanced control rooms (ACRs), become more and more common, which means that the conventional paper-based procedures, hard-wired indicators and analogue controls are being replaced by digital (on-screen, computer-based) procedures, integrated information systems and soft controls, correspondingly. The changes in the HSI impact the work of the operators in several ways and have thus a potential to affect plant safety. However, there are different views about both the quality and quantity of the impacts.

Whether the digital HSIs improve or reduce operator reliability is subject to discussion and research. HRA, as part of the probabilistic risk assessment (PRA), examines the safety of the plant from the point of view of human activity. Human reliability can be defined as the probability of successful performance of a task [Evans 1976] and human errors are regarded as such outputs of human behaviour that fall outside the tolerance scope of the system where a person operates. Human error probability (HEP) is very context-sensitive [Lee et al. 2011a]; when circumstances change, there is a need for re-examination. In addition to the quantification issue, it is also important to explore the new operator performance problems and error modes induced by digital HSIs that differ from those assumed for analogue environments [Massaiu and Fernandes 2017].

Over the years, several HRA methods have been developed both for general use and specifically for the NPP environment, see e.g. [USNRC 2006], [Bell and Holroyd 2009], [Forester et al. 2014], [OECD 2015] for summary reviews. Most of the HRA methods commonly used today were developed before the introduction of ACRs and digital HSIs and thus do not properly account for the changes in the work of the operator induced by the new features of ACRs. Issues that are not specifically addressed by most HRA methods are the impact of different levels of automation, the introduction of on-screen procedures and the human interactions with digital interfaces and soft controls. In HRA such conditions that influence human performance and the HEP of human failure events have been represented by context factors that are referred to by different terms according to the method: PSF (Performance Shaping Factor), PIF (Performance Influencing Factor), PAF (Performance Affecting Factor), EPC (Error Producing Condition), CPC (Common Performance Condition), and so on. These context factors are typically used in adjusting the Basic HEP assumed by the HRA methods [Kim and Jung 2003; Lee et al. 2009]. When used for quantifying the HEP, the word ‘performance’ may indeed seem imprecise since performance can be measured in many different ways that do not directly indicate human reliability (e.g. time taken, operator satisfaction, quality etc.) However, the term PSF is commonly used in HRA literature and is thus used in this paper.

The purpose of this paper is to explore the new challenges posed to the control room operator due to digitalization and present empirical findings on their quantitative effect on human reliability and system safety. The paper aims to give a broader view on the applicability of traditional HRA methods when analysing ACRs and the need for further research in the subject area. Section 2 presents a summary on the effects of digital HSI on the behaviour of control room operators from a human factors point of view. Section 3 presents sets of PSFs suggested in literature and empirical studies on the quantitative effect on PSFs on human reliability. Section 4 discusses the main findings of the review and their implications to HRA and future research agendas. Section 5 concludes the paper.

2. The effect of digital HSI on human behaviour and performance

2.1 Hybrid and digital control rooms

Currently, analogue control rooms tend to be modernised at least partly and the new-builds have digital control rooms to start with. Furthermore, some digital systems in the control room may be redesigned. Thus, digitalization may mean analogue-to-digital migration, digital-to-digital migration or designing totally digital control rooms for new-builds. Thus, in practise, the resulting control rooms may be hybrid, including both analogue and digital features, or completely digital.

ACRs use digital HSI, which is characterised by soft controls, integrated information systems, and on-screen procedures; hybrid control rooms possess only some digital elements, such as the possibility to monitor nuclear processes. Naturally, the new features are expected not to worsen but maintain or rather, improve the working performance of the nuclear operator. However, these radical changes in operating context mean radical changes in the work of the operator as well; the “old” and “new” performances are not directly comparable. The new user interface affects the operator’s tasks, new tasks emerge and the group dynamics and communication are affected. The design decisions of the new system have a strong effect on human performance.

2.2 Evolution of conceptions

Suppositions about the effect of digital user interfaces on operator performance have changed along with the accumulation of experience. As early as 1983, Swain and Guttman [1983], when presenting assessments of occurrences of human errors in NPPs, expected the development of new displays to substantially reduce error probabilities. Next decade, with more knowledge and experience of digital systems, commenting was no longer quite as positive. For instance, Ujita et al. [1995] found in their simulator studies, that the amount of human errors was about the same irrespective of the type of user interface (analogue or digital). More recently, it has been even stated [Hickling and Bowie 2013] that the “belief in the improved human reliability of HCI relative to conventional interfaces” is not substantiated, still requiring considerably more systematic study.

Standards acknowledge the effect of HSI and procedures on operator performance but are rather neutral about the actual effect of digitalization. Thus, according to NUREG-0711 [USNRC 2012], HSI design and procedure development affect human actions (operations in the MCR), which in turn are to be assessed in HRA (see, e.g., page 44 of NUREG-0711). HRA should be involved in the design process early on and the initial HRA, and the set of important human actions, should be finalized when the design of HSI is complete [USNRC 2012]. This means that when the HSI is to be changed, HRA needs to be updated as well. The connection may also work in the opposite direction as “the HRA provides valuable insights into the desirable characteristics of the HSI design” (p.43). Correspondingly, changes in HSI may affect plant HRA as, for example, the original HRA assumptions may no longer be valid for the upgraded design and new errors or new error consequences may emerge with new HSI.

2.3 Unwanted side effects

The influence of human factors (HF) on safety is nowadays recognized in the nuclear domain, and designers are required to consider the operator perspective in the design of new facilities [Papin 2011]. The possibilities to strongly take this perspective into account are ample when thorough modernization of the control room is performed and especially when new plants with ACRs are built. However, the consideration of HF perspective can be restricted to relatively late phases of the projects, even if the design options influencing operator performance would be fixed already during the early phases of the projects [Papin 2011].

Consequently, the possibilities of digital technologies are not necessarily fully exploited to support operator work. Instead, a new solution may affect operator work from a perspective not focused on during the design process. For example, when an operator performs a task at an individual workstation and directly observes the parameters from the display, reporting to other operators may be lessened. Based on both the authors’ discussions with MCR operators and the literature (e.g., [Kaarstadt et al. 2011]), the operators can conclude in an analogue control room what the other crew members operate by seeing where they are located relative to the panels. Thus, the situation awareness may be weaker in an ACR where operators do not move around the MCR to control the processes. This is a situation calling for more, probably deliberate, communication. This requirement, in turn, may increase operators' workload and formal communication may not be as effective as "natural" communication. It has been found, for instance, that experienced crews can maintain their performance under pressure because they provide important information to a crew leader even before he/she requests it; and that communication is the key to create common understanding of the situation [Park et al. 2016a].

A clear advantage with digital HSI is the possibility to provide much more information to operator. This enables the operator to have a deeper understanding of the nuclear processes and to make better informed decisions regarding the controlling of the processes. Especially trends, showing the status of some parameter in a clear and simple way over a long period of time, can provide valuable information about the proceeding of some unwanted phenomenon. The vast amount of information, provided by digital HSI, requires, however, also more capabilities in finding and mastering that information. This tendency has been found by, e.g., Park et al. [2016b] when creating a framework to estimate HEPs from NPP full-scope simulators. The capabilities to find correct information and to master a large amount of information are related to cognitive capabilities. Part of the restrictions in these capabilities cannot be overcome by mental effort but need to be supported by appropriate user interface qualities such as features supporting memory and decision making.

2.4 Weaknesses

Digital solutions can also be designed in a way not really facilitating operator work. For instance, navigation with the digital user interface can be intuitive, with memory supporting functionalities, but it is also possible that operators learn to navigate effectively and efficiently only after extensive training and/or with experience, with trials and errors. Similarly, on-screen procedures can have effective place-keeping functions to prevent the loss of operator's position in the procedure, but the place-keeping functions may also be ineffective due to unclear markings, especially when performing parallel paths in a procedure.

New weaknesses related to digital solutions could perhaps be, in principal, mitigated or removed by careful design by taking the operator perspective strongly into account. The key question is, as it has always been, how to guarantee that all important factors are appropriately taken into account in each specific design case. For instance, when Mumaw et al. [2000] studied how operators monitor plant state during normal operating conditions, they found that even in this non-demanding operational context, the monitoring is based on active problem solving. The available means (related to the user interface) were used in accordance with the plant's situation – the situation which is both complex and dynamic as, for instance, each unit in an NPP consists of thousands of components and instruments. Even though the equipment is reliable as such, failures are bound to occur due to the high number of components. Furthermore, some failures can be repaired only during the shutdown of the unit. In addition, human cognitive capabilities, regarding both restrictions and possibilities, should be taken into account when evaluating the qualities of an HSI. Not astonishingly albeit interestingly, Mumaw et al. [2000] end up suggesting that operators are provided with a possibility to create user-defined auditory cues for the alarm system.

2.5 Digitalization - source of improvement or new types of flaws?

Due to the fact that an NPP is composed of a high number of components and numerous systems that can be monitored and controlled via various types of user interfaces, it is not possible to state on a sound basis that, say, paper based or on-screen procedures are better as such. The way in which the digital possibilities are used in the solution affect decidedly its quality and appropriateness. For instance, on-screen procedures can be direct translations from paper-based procedures to digital ones, without any added functionality; and if new functionalities are embedded in the on-screen procedures, the functionalities are not necessarily of the kind which only bring benefit to the human operator. As an example, it has been found that such on-screen procedures, which provide automated guidance about the success of each step, may even reduce the effectiveness of operator checks [Taylor et al. 2017].

The new error potentials, brought by digital solutions, seem thus be related to flaws, biases etc. in the user interface, such as insufficiently realised functionalities which could support operator work in principle but do not actually do so, or dysfunctional new features, which may lead the operator astray, or the side-effects of the new user interface, such as the reduction of communication within the crew or the difficulty in mastering the large amount of information.

Correspondingly, the studies over hybrid and digital control rooms and related operator tools provide various, sometimes even contradicting results (see Table 1). It is not possible to evaluate unanimously the pros and cons of analogue and digital control rooms.

Perhaps the main difference between all analogue and digital HSI's is the introduction of new secondary tasks; along with digital HSI, new interface management tasks appear (navigation through menus to reach the desired target etc.). The effect of secondary tasks protrude through all operating activities performed in the ACR. According to O'Hara et al. [2002], this has two negative effects on the work of the operator: (1) primary task performance, i.e., the actual process monitoring and control, declines because operator attention is directed toward the interface management task, and (2) under high workload, operators minimize their performance of interface management tasks, thus failing to retrieve potentially important information for their primary tasks. Further, these effects were found to have potential negative effect on safety. The results of O'Hara et al. [2002] have been replicated by Zhang and Zou [2016] and also other studies on secondary tasks have been performed. For instance, possible errors when using soft controls have been classified into six error modes of operation omission, selection of wrong object, performing a wrong operation, mode confusion, inadequate operation (too early/too long/too short) and delayed operation (e.g., [Lee et al. 2011a]). Even if the error modes are somewhat similar to the ones of conventional controls, their causes are different. For instance, a wrong object (e.g., button to push) can be selected on both right and wrong screen. Julius et al. [2014] consider the following possible new error modes to be specifically related to digital control systems: selection of wrong controls (same 'look-and-feel' for all components); and selection errors in reading indications (e.g., lack of differentiation between safety and non-safety components). Additionally, operator errors could occur if there is an error or system failure that is not readily apparent such as a software operating system error or coding error.

All in all, analogue and digital user interfaces may introduce challenges in operator performance characteristic to the type of interface in question, but many similar problems seem to reside in all of them. Park et al. [2015] studied the characteristics and differences between operator performances related to the three types of control rooms: analogue, hybrid and digital control rooms as reported in published reports. Even if, understandably, differences were found, there was ample information about similarities as well. The main categories in which all types of control rooms raised issues by Park et al. [2015], i.e., the cross-cutting human performance issues, are the following: HSI complexity, situation assessment, cognitive workload, physical workload, crew performance, opacity in a digital system, dealing with diverse information across different sources, fatigue due to digital environment, and confirmation/trust on a (digital) system.

The digital aspects are not necessarily restricted to the user interfaces only. Also automation can be digitalised and the level of automation can be raised, with the assumption that along with this process, human operators have less opportunities to make errors. This assumption is not entirely valid as, for instance, increased automation can challenge the operator's situation awareness [Endsley 1996]. Automation can also reduce the operator's vigilance, trust in automation may lead to failure to manually check automated actions, etc. Human errors can be considered as results of the normal functioning of a human being; if designers expect humans to act like machines, the designers are the ones making the error [Schutte 2017]. Furthermore, from another perspective, humans may be "accused" for errors that are made due to poor design. For some reason, it is easily considered that human users could compensate for poor design when it would be more effective to improve the design. High level of automation and lacking transparency from the operator perspective, resulting in insufficient situation awareness and ultimately, inability to act if automation fails, can be regarded an example of such a design error. As a whole, further work is needed to understand the impact of automation upon reliability and it is an issue of a study of its own.

2.6 Suggestion for the effects of digitalization

The levels of appropriateness of the implemented digital solutions vary from one case to another. They can be scrutinised from a single functionality point of view, such as alarm system, team communication etc. or from a larger perspective. An example of the latter is the study of Liinasuo and Porthin [2014], who investigated the error types occurring in an ACR, utilizing error descriptions gathered during HF oriented design phase validation. The validation was focused on the usage of on-screen procedures and the related digital user interfaces for monitoring and controlling the process, located on different displays in the control room. They identified 484 issues (HEDs, Human Ergonomics Discrepancies). The majority were display related issues (71%), and the rest were classified as concept-level (26%) or performance-demand related issues (3%). On the other hand, when analysing HF issues related to ACR, Lee et al. [2011b] identified 46 HF issues related to computerized procedure system (CPS), acquisition of HSI information, HSI control and training. The results, or issues found, probably vary in accordance with both the system in question and the focus of the research.

Zhang and Zou [2016] found that digital user interfaces have greatly changed the way the operators access, storage, process and output the information. Also, more emotional aspects such as stress and workload should be taken into account. The amount of all possible displays, contrasted with the outlook with which an experienced operator can gain the big picture of the plant's processes, may increase simultaneously the amount of available information and workload. Furthermore, team performance related factors such as collaboration, coordination, and communication are essential viewpoints.

It can be concluded that a majority of the effects of control room digitalization on human behaviour and performance depend on the specific system design and its realization. However, some effects seem common for ACRs regardless of the specific design:

- Digital systems provide more information to the operator than the analogue one
- The digital user interface brings new secondary tasks compared to the analogue one
- With a digital user interface, the operator is not self-evidently aware of what other operators are doing whereas with analogue user interface, the location of the operators relative to the panel

shows directly what system the operator is manipulating (but this information can be provided by digital means)

- Digital systems tend to be more frequently updated due to shorter life cycles of digital software and hardware - this sets more pressure to plant design and the related training.

Table 1 Examples of studies of hybrid or digital control rooms based upon responses by experienced operators.

Reference	Research method	Result
Ujita et al. [1995]	Simulator tests for several fault conditions during several operator shifts.	The number of errors is about the same with analogue and digital interface.
Converse [1995]	Simulator study where the use of paper-based and digital procedures was compared in simulated emergency situations.	There was no distinction between performance times in the LOCA[1] situation, but the number of errors was significantly higher when using paper-based procedures.
Hallbert et al. [1997]; Sebok [2000]	Simulator study where the operators' performance was compared between ACRs and in traditional ones in simulated emergency situations.	In the ACR, the performance was better in all situations related to transient management tasks.
Roth and Patterson [2000]	Simulator study where five crews were followed in simulated situations and the operators were interviewed afterwards.	The operators considered the new (digital) interfaces to improve their situation awareness and performance.
Vicente et al. [2001]	Field study where the activities of 11 operators were monitored during 88 hours in a hybrid control room.	The same information sources were used in the modern control rooms and in the old ones, but what information was sought and how varied. In the new hybrid control room, alarm screens were used more than before for problem detection. In the new control room, the operators move less than earlier from their desks.
Andresen et al. [2004]	Simulator study where the use of procedures was explored in four situations: 1) paper-based procedures, 2) manual digital procedures, 3) procedures, where the implementation was partly automated, and 4) procedures with completely automated implementation.	The operators did not like the completely automated implementation of the procedures. In this situation, their understanding of the current status was weak. This did not lead to deterioration of their performance. Instead, they found that procedures where the implementation was partly automated were suitable for certain situations.
Min et al. [2004]	Simulator study where the use of paper-based or digital procedures were compared in simulated primary circuit leakage accidents.	Intermediate communication decreased considerably with digital procedures, and the role of the shift manager was emphasized. The procedure type also influenced communication: With digital procedures, shift managers asked more confirmation for their own observations from other operators.
Kaarstadt et al. [2011]	Workshops with the operators of the power plants to gather experiences about ACRs	In ACRs, it is harder for the operators to know what the others are doing. They need to discuss more, which may increase their workload. It is also more difficult to get an overview of the current state of the process.

Hwang et al. [2009]	A survey where 25 operators were interviewed about their experiences on ACRs based on workstations in Taiwanese NPPs.	Some operators considered supervision and operation to be easier in display-based control room as the instructor can take all necessary steps using the same screen. Other operators again think that this feature complicates the operation, because certain information cannot directly be found on a specific screen.
Kim et al. [2011]	Simulator study where operator performance was compared between traditional and digital control rooms in simulated accident situations.	Event diagnosis time seemed to differ between traditional and digital control room depending on event type (LOCA[1]: trad: 136 s - dig: 134 s, SGTR[2]: trad: 196 s - dig: 141 s, ESDE[3]: trad: 182 s - dig: 280 s.). The differences are not statistically significant due to small sample size. One error was made in ACR due to wrong indication presented on personal screen. In traditional control room the data acquisition would have required communication, during which the instrument unavailability could have been identified. Error recovery potential was higher in ACR due to new information sharing and access capabilities.
Laarni and Liinasuo [2012]	Simulator tests for LOCA[1], PRISE[4] and loss of bus bar in main (hybrid) control room.	The operators considered the usability of the control room to be good; process computer displays and especially the trends were good, although the information was often visually confused and illogical. The way of use and the benefits gained varied between shifts. The number of alarms was too high.
Laarni and Liinasuo [2012]	Simulator tests for loss of system 321 (shutdown cooling system), ejector fault and a failure of preheater.	The operators were generally quite satisfied with the usability of the hybrid control room. They considered the logic of some displays not to be understandable (action diagrams), which can prevent rapid response. Movement in the control room and navigation in the displays took a lot of time. There were many problems in the digital interface solutions: The large screen view was practically not used at all and the screens of the turbine operator needed further development. The number of alarms was too high.
Lin et al. [2016]	A within-subjects experiment was designed for a simulated scenario of an ACR and then a survey was conducted.	The teams had better objective performance, higher situation awareness, lower human error and lower communication rates when using digital procedures.
Liu and Li [2016]	The survey compared conventional and digital MCRs in NPPs from a task complexity perspective. A total of 69 licensed operators participated in the study.	Operators in ACRs perceived higher frequency and higher impact of complexity factors than those in conventional MCRs, in all (abnormal/emergency and normal) situations. Operators in ACRs perceived higher complexity than those in conventional MCRs in abnormal/emergency situations.

Massaiu and Fernandes [2017]	Simulator study where operators answered questions requiring identification of plant parameter status on 1) plant panels 2) tablet-based digital overview-displays.	The operator error rate is more dependent on task type than on the HSI. HSI effect on the error rates was not statistically significant. The differences in error rates were significantly different across task types.
Zou et al. [2017]	Case Study on the LingAo II, the first digital NPP in China to apply state oriented procedures. Experimental research as well as qualitative and quantitative analysis were used. Operator behaviour patterns and characteristics were studied via behavioural observation, questionnaire survey, and comparative analysis. Simulation experiments and HFE experiments were carried out to investigate the factors and mechanisms affecting operators' cognitive behaviour. Human reliability data were obtained using a testing method, statistics method, expert judgment, review of original data, and extrapolation.	Cognitive load in collecting and integrating information has reduced because the operators have more available information about the system and they can combine the information in a more flexible way to determine the system state. Operators' role has changed from manual controllers to supervisors of an automated system and primary tasks have changed from operation to monitoring and decision making. Need to perform interface management tasks increase the cognitive load and working load of operators, which has increased the chance of human error occurring, such as loss of situation awareness and mode confusion. Increase of cognitive load has brought new risks during performance of primary tasks, such as decreasing information verification and focusing on specific operations. Errors of commission have seen a significant increase; the display and distribution of information in the ACR more easily lead to errors of omission. The operators have strong preferences, such as ignoring some procedures habitually and operating behaviours are hard to observe by other operators unless a mistake leads to feedback. The number of human factor events has relatively increased due to the lack of supervision.

[1] Loss of coolant accident, [2] Steam generator tube rupture, [3] Excessive steam demand event, [4] Primary to secondary leakage

3. Performance shaping factors for advanced control rooms

3.1 Performance shaping factors

Most HRA methods use PSFs to characterise the context of human tasks, which is assumed to affect their HEPs. Although there are commonalities in PSFs from one method to another, the field is far from standardised. Not only are different HRA methods accounting for different contextual factors, but the PSF taxonomies differ and the PSFs are being defined and measured in different ways in different methods.

Recommended PSFs can be found in guidance and standards documents [IAEA 2016; ASME/ANS 2009; USNRC 2005]. In addition, several researchers have presented their own views on optimal PSF taxonomies [Lee et al. 2011b; Kim and Jung 2003; Park et al. 2014; Liu et al. 2016; Groth and Mosleh 2012].

3.1.1 Guidance on PSFs

The IAEA-TECDOC-1804 [IAEA 2016] and the ASME/ANS standard [ASME/ANS 2009] for Level 1 PSA as well as NUREG-1792 Good Practices for Implementing HRA [USNRC 2005] provide requirements or good practices of a general nature regarding identifying, modelling and quantifying post-initiator human actions and adding recovery actions to the PRA. All three sources list quite similar post-initiator PSFs to be considered both for control room and local (ex-control room) actions. These are summarized in Table 2.

Table 2 PSFs required or recommended by IAEA, ASME/ANS and NRC to be considered when assessing post-initiator human actions.

PSF	IAEA-TECDOC-1804	ASME/ANS	NUREG-1792
Available and required time	x	x	x
Quality of procedures and administrative controls	x	x	x
Availability of instrumentation	x	x	x
Clarity of cues/indications	x	x	x
Training and experience	x	x	x
HSI	x	x	x
Task complexity	x	x	x
Working environment	x	x	x
Accessibility of equipment	x	x	x
Communication	x		x
Crew dynamics and interaction	x		x
Staffing and resources			x
Need for and availability of special tools		x	x
Distractions caused by parallel tasks	x		
Workload, time pressure, stress			x
Special fitness needs			x
Consideration of “realistic” accident sequence diversions and deviations			x

3.1.2 PSF taxonomies

Lee et al. [2011b] performed a review of existing PSFs used in HRA methods, with the aim to develop a qualitative framework for PSFs in ACRs. They collected and reviewed 159 PSFs from nine HRA methods: THERP [Swain and Guttmann 1983], SLIM [Embrey et al. 1984], INTENT [Gertman et al. 1992], HEART [Kirwan 1996], CREAM [Hollnagel 1998], HRMS [Kirwan 1997], SPAR-H [Blackman 2008; Boring and Blackman 2007; Gertman et al. 2005], ATHEANA [Forester et al. 2007], and IDAC [Chang and Mosleh 2007a; Chang and Mosleh 2007b]. The reviewed PSFs were mapped into nine main categories: stress level, action type, experience, time constraints, places where operator actions are taken, procedures, training, HSI, and team factor. The PSF mapping shows differences in the scope of the HRA methods, the number of covered categories in the methods ranging from five to nine. There is also a variety in the naming of the PSFs, and in their definitions.

Kim and Jung [2003] collected approximately 220 PSFs from existing taxonomies and other literature in order to form a new full-set PSF taxonomy. They reviewed seven detailed sets of PSFs (which they call full-set PIFs): CSNI taxonomy [Rasmussen et al. 1981], THERP [Swain and Guttman 1983], HEART [Williams 1988], PHECA [Whalley 1987], PSF taxonomy [Bellamy 1991], Influencing factors [Gerdes 1997], K-HPES [KEPRI 1998] and eleven taxonomies used in HRA methods: SLIM [Embrey et al. 1984] & PLG-SLIM [Chu et al. 1994], INTENT [Gertman et al. 1992], IDA [Phillips et al. 1990], HRMS [Kirwan 1997], Macwan's [Macwan and Mosleh 1994], Julius' [Julius et al. 1995], CREAM [Hollnagel 1998], INCORECT [Kontogiannis 1997], Taylor-Adams' [Taylor-Adams 1995], Rogers' [Gibson et al. 1998], and ATHEANA [USNRC 2000]. They collated the PSFs into four main groups, which they defined as follows:

- HUMAN: Personal characteristics and working capabilities of the human operator.
- SYSTEM: Man-machine interface (MMI), plant hardware system, and physical characteristics of the plant process.
- TASK: Procedures and task characteristics required of the operator.
- ENVIRONMENT: Team and organization factors, and physical working environment.

They divide each main group into several subgroups, which in turn contain several detailed items. They concluded that a majority of the HRA methods used PSFs for training, experience, procedure, MMI/information, and time, and that a moderate share of the methods use PSFs for stress, workload, motivation, task complexity, simultaneous goals/tasks, working condition, supervision, team factors, and communication. There were also PSFs used only by a minority of the HRA methods, such as adequacy of resources, decision making criteria, response dynamics and system coupling, availability of equipment, trend and value of critical parameters, time of day, organization factors, task organization, and safety culture. Out of the full-set PSF Kim and Jung [2003] defined a set of PSFs for human error analysis of accident management tasks by considering situational characteristics and human factors under accident management and a set of good practices when selecting PSFs. The proposed set of PSFs is shown in Table 3. Park et al. [2014] presented another PSF categorization based on the PSF set by Kim and Jung. They then further compiled a set of HRA data items relevant for simulator studies by completing the PSF list with items found from HRA and human factors standard and recommendation documents.

Liu et al. [2016] developed a full-set PSF model with the aim to identify the key PSFs in ACRs. They extracted PSFs from HRA methods, human performance database, human event reports, and other sources. They defined eight PSF Components: Operator, Crew, Organization, HSI, System, Working Environment, Procedure, and Task. The components were divided into 30 PSF Factors and further into 140 PSF Indicators. Table 3 shows the PSF Components and Factors.

Groth and Mosleh [2012] proposed a set of PSFs for causal modelling by aggregating information from IDAC [Chang and Mosleh 2007a; Chang and Mosleh 2007b], retrospective data, expert workshops, and the HRA methods CREAM [Hollnagel 1998], SPAR-H [Blackman 2008; Boring and Blackman 2007; Gertman et al. 2005], CBDT [Parry et al. 1992], THERP [Swain and Guttman 1983], and HEART [Williams 1988]. The two highest levels of the hierarchical PSF set are presented in Table 3.

The five PSF taxonomies are presented in Table 3 and arranged according to the PSF categories of Table 2. It can be seen that although arranged a bit differently, all of the taxonomies include quite similar factors. No equivalents for the categories *Need for and availability of special tools*, *Special fitness needs* or *Consideration of "realistic" accident sequence diversions and deviations* from Table 2 were found in the taxonomies. Instead they included a more complete set of organizational factors, including e.g. plant policy and safety culture. Also different properties of the system are included in four of the taxonomies. Only the two top levels of the hierarchical PSF taxonomies are shown in the table, thus some lower level issues remain unpresented here.

Table 3 Mapping of PSF taxonomies to the categories of Table 2. The categories marked with * are not found in Table 2.

PSF category	Lee et al. [2011b]	Kim and Jung [2003]	Park et al. [2014]	Liu et al. [2016]	Groth and Mosleh [2012]
Available and required time Workload Time pressure Stress	Time available Stress	SYSTEM – Time pressure	OPERATOR CHARACTERISTICS – Physical/physiological SYSTEM – Operational characteristics (available time, time pressure)	OPERATOR – Fatigue – Stress TASK: – Time pressure	PERSON – Attention – Physical & physiological abilities SITUATION/STRESSOR – Time load – Stress – Perceived situation
Quality of procedures and administrative controls	Procedure	TASK: – Availability and quality of procedures	TASK: – Task contents (Procedures)	PROCEDURE – Procedure complexity – Procedure quality	ORGANIZATION: – Resources (Procedures)
Availability of instrumentation Clarity of cues/indications HSI	HMI	SYSTEM – Availability and quality of information	HMI – Indicator/controllers – Panel/screen layout – Support system	HSI – Information availability – Information ambiguity – Information unreliability – Information overload	MACHINE – HSI
Training and experience	Training Experience	HUMAN – Training and experience	OPERATOR CHARACTERISTICS – Cognitive ORGANIZATION – Training related	OPERATOR – Experience/training/skill	ORGANIZATION – Training program PERSON – Knowledge/experience – Skills – Familiarity with situation
Task complexity Distractions caused by parallel tasks	Action type	TASK – Simultaneous goals/tasks – Task type/attributes	TASK – Task type/attribute – Task contents	TASK – Goal complexity – Information acquisition complexity – Information analysis complexity – Decision making complexity	SITUATION/STRESSOR – Conditioning events – Task load – Other loads – Task complexity

				– Action implementation complexity	
Working environment Accessibility of equipment	Places where operator action are taken	ENVIRONMENT – Working environmental features	ENVIRONMENT – Task related – Working condition related	WORKING ENVIRONMENT – Habitability – Workplace quality	SITUATION/STRESSOR – External environment
Communication	Teamwork	ENVIRONMENT – Team cooperation and communication	ORGANIZATION – Communication related	CREW – Communication requirement – Communication availability – Communication quality	TEAM – Communication
Crew dynamics and interaction	Teamwork	ENVIRONMENT – Team cooperation and communication	ORGANIZATION – Team related	CREW – Leadership – Team cohesion – Team coordination	TEAM – Direct supervision – Team coordination – Team cohesion – Role awareness
Staffing and resources Organizational factors*	-	ENVIRONMENT – Plant policy and safety culture	SOCIAL ASPECTS OPERATOR CHARACTERISTICS – Personal ORGANIZATION – Management/policy related – Safety culture related	OPERATOR – Responsibility – Bias ORGANIZATION – Safety culture – Resource management	PERSON – Bias – Morale/motivation/attitude ORGANIZATION – Corrective action program – Other programs – Safety culture – Management activities – Workplace adequacy – Resources – Role awareness
System*	-	SYSTEM – Status and trend of critical parameters – Status of safety system/component	SYSTEM – System state – Physical characteristics	SYSTEM – System unreliability – System complexity – System dynamics	MACHINE – System response

3.2 Empirical studies on PSF effects in ACRs

The main sources of human error data used for informing HRA methods on e.g. PSF effects are documented operating experience, observations from full-scope and limited scope simulator studies, expert judgements and interviews with subject matter experts [IAEA 1998; Ham and Park 2018]. Sources for documented operational experience include e.g. event, near miss and maintenance reports, equipment records and plant log books. While operating experience reflects the real situation, many relevant data are often not properly recorded or not even observable in real-life situations. For example, information about environmental conditions and the number of successfully performed tasks may be hard to retrieve. Also, data for analysing rear events are usually very scarce or even non-existing. Interviews with subject matter experts are highly recommendable and certainly help the HRA analyst in understanding the phenomena on a qualitative level, but the benefits for quantification may be limited. The main advantages of full-scope simulator studies are that they provide an environment and human behaviour similar to the real world, but in the same time controllable and observable conditions.

It has been argued that HEP quantifications for ACRs rely too much on information inherited from old methods and subjective judgements and that more focus should be put on empirical studies [Hickling and Bowie 2013; Boring 2014]. It has also been suggested that traditional methods such as THERP may have always been optimistic in their HEP assessments or that tasks based on digital HSIs would in general be less reliable than tasks on analogue interfaces [Hickling and Bowie 2013]. Other studies suggest that tasks based on digital HSIs would inherently be more reliable than on analogue interfaces due to new guiding features in the procedures, e.g. place-keeping aids and check-off provisions [Dirksen and Eisinger 2017].

As the result of a search on empirical studies on the effect of PSFs on HEP values in ACRs, six studies reported in scientific publications between 2008 and 2018 were found, all of them dealing at least partly with ACRs, see Table 4.

3.2.1 Test settings

Three of the studies were performed on modern ACR simulators [Park et al. 2017; Kim et al. 2015; Kim et al. 2018], one used a system and HSI simulated on computers [Xu et al. 2008], one comparative study was carried out on analogue simulator and tablet computers [Massaiu and Fernandes 2017] and one relied on operational experience from Korean NPPs including both analogue and digital MCRs [Ham and Park 2018]. Two of the studies used university students, whereas licensed operators were used in the other ones. In general, a set of PSFs were defined as independent variables in the studies and one or more performance measures as dependent variables. The main aim of Kim et al. [2018] was to estimate the probability of diagnosis error in ACRs by Bayesian updating of the THERP time reliability correlation (TRC) model developed for analogue control rooms. In order to obtain nominal probabilities of diagnosis errors to be used in the Bayesian updating, it was necessary to assess the effects of PSFs. Here only the quantitative analysis of the PSF effects is addressed.

Some of the studies considered only one type of human error, such as deviation from procedures, faulty identification of system state or diagnosis error, whereas some of the studies considered several types of errors and analysed the PSFs separately for each of them. The test scenarios ranged from simple micro tasks concerning identification of system state without any scenario context to accident scenarios such as variations of steam generator tube rupture (SGTR), loss of offsite power (LOOP), loss of coolant accident (LOCA), excessive steam demand event (ESDE), loss of all feed water/total loss of feed water (LOAF/LOFW) or station black out (SBO). The study based on operational experience by Ham and Park [2018] did obviously not consider any predefined accident scenario, but examined different types of operator errors that had been reported in event investigation reports.

Each study focused on a different set of PSFs as independent variables, see Table 4. Training or experience was included in all simulator studies and some characterisation of the HSI was included in most of the studies. Also task type or complexity was a reoccurring PSF. It can be argued that task type should really be treated as part of the generic task type definition. However, in part of the studies task type was treated as one of the independent variables in the analysis, and in such cases it is reported here as one of the PSFs. In most of the cases the PSFs were defined as binary variables (e.g. *normal* / *poor*), although in most HRA methods, PSFs can attain several values (e.g. 1 – 5).

Error rate was used as a performance measure (i.e. dependent variable) in all of the studies. In addition, operation or response time was included in three studies. Other measures deployed were NASA task load index (TLX), time to enter cool down of RCS (Reactor Coolant System), number of secondary tasks, workload and situation awareness.

3.2.2 Analysis methods

The reviewed studies used analysis of variance (ANOVA), logistic regression, a simple profiling technique or a big data analysis technique called classification and regression tree (CART) as their main quantitative analysis method for assessing PSF effects. ANOVA, applied in Xu et al. [2008], Park et al. [2017] and Massaiu and Fernandes [2017], can be used to assess which potential PSFs have a statistically significant effect on the performance of the operators. Combined effects of the PSFs may also be analysed. ANOVA does not give a direct answer on the magnitude of effect of the independent variables on the dependent ones, but rather indicates the statistical significance of the independent variables.

Logistic regression, applied in Kim et al. [2015], can be used to derive the quantitative effect of the examined PSFs and combinations of PSFs on human performance. Formally, the logistic regression model used by Kim et al. is

$$\boldsymbol{ln\frac{p(x)}{1-p(x)} = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n,} \tag{1}$$

where $p(x)$ is the HEP and β_0, …, β_n are regression coefficients that represent the effects of independent variables $x_1, \ldots, x_n$ on the logarithm of the odds ratio transformation of $p(x)$. Solving the equation with regard to the probability $p(x)$ yields:

$$\boldsymbol{p(\mathrm{x}) = \frac{\mathrm{exp}^{\beta_0+\beta_1 x_1+\cdots+\beta_n x_n}}{1-\mathrm{exp}^{\beta_0+\beta_1 x_1+\cdots+\beta_n x_n}}} \ . \tag{2}$$

If there are enough data available, the effects of the PSFs (β_i) can be estimated using the Maximum likelihood method. Standard regression analysis techniques allow for e.g. assessment of the significance of different independent variables (PSFs). Variable selection strategies such as forward selection, backward selection and stepwise selection as well as variable selection criteria such as adjusted R^2, Mallow's Cp, AIC (Akaike Information Criterion), BIC (Bayes Information Criterion) and PRESS (Predicted Residual Sum of Squares) may also be used.

The quantification of PSF weights in Kim et al. [2018] was done using a profiling technique suggested by Kirwan [1997] assuming that the effects of the PSFs are independent from each other. First, the probabilities of diagnosis error in each task were calculated by dividing the number of errors with the number of error opportunities. For tasks with zero observed errors, the HEP was calculated using Eq. (3):

$$p = 1 - 0.5^{\frac{1}{m}}, \tag{3}$$

where p is the HEP and m is the number of trials. Tasks with different PSF values could then be compared. E.g. if only one PSF differs between two tasks and the rest of the PSFs are equal, the effect of that PSF could be estimated as the ratio between the HEPs of the two tasks. It is assumed that tasks where all PSF values are equal have the same underlying HEP. Kim et al. [2018] did not assess the uncertainties of the estimated PSF effects, which may indeed be considerable due to the quite small amount of data, nor the statistical significance of the PSFs.

A slightly similar approach to the profiling technique was applied by Ham and Park [2018] to extract HRA data from event investigation reports. They organized reported failure cases and estimated numbers of successful cases with regard to a set of PSFs using the CART technique. The HEP for each path in the decision tree, representing different combinations of PSF values, were calculated by dividing the number of failures with the total number of cases (successes and failures) with the same set of PSF values. In contrast to the profiling technique, here the effect of a PSF was estimated by calculating the ratio between the HEP in cases where the PSF attains a certain value (e.g. *high*) with the one where it attains the complement value (e.g. *low*) irrespectively of the values of the other PSFs. Effects of combinations of PSFs were also assessed by comparing the HEPs between different decision tree paths. Although the data included both cases with analogue and digital HSI, the effects of other PSFs were not analysed for ACRs separately. However, the effect of analogue vs. digital HSI was assessed. As Kim et al. [2018], Ham and Park [2018] did not assess the statistical significance of their results. A systematic approach to collect essential information from the event investigation reports and success cases was also developed, see [Ham and Park 2018] for further details.

3.2.3 Main conclusions of the empirical studies

Training or experience was examined in four studies, which all concluded that it has an effect on human performance, either on its own or in form of combined effects with another PSF. According to Xu et al. [2008], training level influences all the examined performance measures: error rate, operation time and subjective workload (TLX). Park et al. [2017] has also found that operator experience affects operation time, error rate and workload, and in addition the time to enter cool down of RCS. Kim et al. [2015] conclude that the combined effect of no training and no subsystem description increases the probability of wrong screen switch by a factor of 2.90 and the combined effect of no training and continuous operation type increases the probability of wrong mode conversion by a factor of 3.45. The results by Kim et al. [2018] suggest that the PSFs for training and experience for diagnosis errors in ACRs are slightly lower than those in THERP.

Four of the studies indicate that task complexity, task type or operation type affects human performance. Xu et al. [2008] suggest that task complexity affects error rate and operation time, while Park et al. [2017] suggest that it affects the number of secondary tasks and situation awareness, but has no effect on error rate and operation time. Massaiu and Fernandes [2017] show that task type has a statistically significant effect on the error rate of micro tasks. They have also compared the observed relative error rates of the different task types to the ones assumed in KAERI's classification of Unsafe Acts [Park et al. 2016b] and in THERP's table of estimated HEPs (tables 20-10 and 20-11 in [Swain and Guttmann 1983]). Interestingly the observed relative differences in error rates were inconsistent with the relative differences assumed by KAERI and THERP, but no explanations for the differences were given. Also, the observed error rates for the isolated micro tasks without a broader context were much higher than the ones assumed by the HRA methods. As mentioned earlier, Kim et al. [2015] found a negative combined effect of no training and continuous operation type. Kim et al. [2018] included action type in their analysis but did not report any results on the specific PSF.

Procedures were examined in four of the studies, although the reported results in [Ham and Park 2018] were not specific to ACRs. Xu et al. [2008] found that emergency operating procedures (EOP) with both one- and two-dimensional flowcharts as well as brief instructions and system parameters resulted in lower error rates than a briefer EOP style with a two-dimensional flowchart and a success tree. In the former style, the one-dimensional flowchart listed all the steps of an EOP, with the current step highlighted, while the two-dimensional flowchart described the detailed logical structure of the current step. In the latter, the two-dimensional flowchart was briefer than in the other style and detailed information of the current step was given by the success tree and text instruction. Kim et al. [2015] found that information on the related subsystem in the procedures lowered the error rate for wrong screen switch and that explicit description whether the control mode is to be converted or not lowered the error rate for wrong mode conversion. Kim et al. [2018] reported a 2.50 factor for *Poor* vs. *Good* procedures. Ham and Park divided issues related to procedures in several PSFs, such as *Procedure conformity*, *Clarity of decision-making criteria*, *Clear description of an object* and *Clear description of means*, which were reported factors between 12.0 and 27.5 (*No* vs. *Yes*). However, these results are not specific to ACRs, although such results would apparently have been possible to extract from the data.

Massaiu and Fernandes [2017] and Ham and Park [2018] studied the effect of HSI type (analogue vs. digital) on operator performance. In [Massaiu and Fernandes 2017] the ability of an operator to correctly identify the system state was in focus, leaving control and procedures outside the study. However, the study did not find any statistically significant effect of the HSI type on the error rate. In contrary, Ham and Park [2018] reported ten times higher HEPs for tasks with digital HSI compared to analogue.

Kim et al. [2018] reported also notable magnitudes for the PSFs *Teamwork* (PSF = 11.00, *Poor* vs. *Good*) and *Time constraint* (PSF = 3.00, $T \leq 20$ *min* vs. 20 *min* $< T \leq 40$ *min*, where T is available time for diagnosis). However, as noted in Section 3.2.2, Kim et al. [2018] and Ham and Park [2018] did not assess the statistical significance of their results.

Table 4 Empirical studies on the effect of PSFs on human performance in ACRs.

Study	Analysis method	PSFs (independent variables)	Performance measures (dependent variables)	Error types	Test setting	Scenarios	Main conclusions
Xu et al. [2008]	ANOVA	EOP presentation style Task complexity Training level	Operation time Error rate Nasa TLX (task load index)	Deviation from procedure	Undergraduate university students and a simulated system with on-screen EOP	Shortened SGTR[1] procedure Shortened emergency shutdown procedure	All three PSFs influence error rate. Task complexity and training level influence operation time. Training level influences subjective workload.
Park et al. [2017]	ANOVA	Operator experience Task complexity Time urgency	Operation time Error rate Time to enter cool down of RCS Number of secondary tasks Workload Situation awareness	Deviation from procedure: omission and commission errors (recoveries not accounted for)	Licensed operators and an APR1400 simulator (ACR)	1. Inadvertent opening of an ADV[2] + LOOP[3] 2. SGTR[1] + Failure of N16 indicators (Masking of information) 3. LOCA[4] + Failure of safety injection system 4. Small break LOCA[4] 5. ESDE[5] + Failure of N16 indicators (Masking of information) 6. LOAF[6]	Operator experience affects operation time, error rate, time to enter cool down of RCS and workload. Task complexity influences the number of secondary tasks and situation awareness. Time urgency does not influence operator performance.
Kim et al. [2015]	Logistic regression	Subsystem description (SD) Practice level (PR) Safety (SA)	Error rate	Errors with soft controls: Step omission	Graduate students and computer-based Westinghouse type PWR simulator	SGTR[1] accident	Commission error more frequent than omission.

		Operation type (OP) Mode conversion (MC) Ambiguous description for mode conversion (AD) The number of subtasks (SN) The number of secondary operations (SON) Also combined effects analysed		Wrong screen switch Wrong device selection Operation omission Wrong operation Inadequate operation Wrong mode conversion Confirmation omission			Most frequent errors and their most significant PSFs: Wrong screen switch (SD, SD&PR) and Wrong mode conversion (AD, OP&PR). No significant PSFs selected for other error types, mostly due to low number of observed errors. Numerical odds ratios estimated for the PSF effects
Massaiu and Fernandes [2017]	ANOVA	HSI type (analogue vs. digital) Task type	Error rate Response time	Identification of system state	16 licensed operators, Simulator snapshots of ECCS[7] and RCS[8]. Analogue: existing boards in simulator, Digital: 12" tablet computers Questions answered using tablet computer	Micro tasks (19 ECCS[7] and 17 RCS[8] questions)	HSI type: not statistically significant. Task type: statistically significant. Relative error rate differences for task types inconsistent with relative differences assumed by THERP and KAERI.
Kim et al. [2018]	Profiling technique assuming independent PSFs	Stress level Action type HSI Time constraint Place where the action is taken Procedure	Error rate (observed errors vs. error opportunities)	Diagnosis error	Licensed PWR crews and full-scope ACR simulator; In addition data from HAMMLAB full-scope PWR simulator with licensed crews	LOCA[4], SGTR[1], SBO[9] HAMMLAB: SGTR[1], LOFW[6] (each with base case and complex case)	Estimated weights for each PSF, no assessment of statistical significance. Largest factors: Teamwork,

		Training Experience Teamwork			(International Empirical Study)		Procedure, Time constraint
Ham and Park [2018]	CART big data analysis	27 PSFs including e.g. HSI type	Error rate	Wrong device operation Omission of a procedural step Providing wrong control input	16 Korean event investigation reports and estimated numbers of corresponding success cases	Full power operation	10 times higher error rate for digital than analogue HSI. Results for other PSFs not reported separately for ACRs. No assessment of statistical significance.

[1] Steam generator tube rupture, [2] Atmospheric dump valve, [3] Loss of offsite power, [4] Loss of coolant accident, [5] Excessive steam demand event, [6] Loss of all feed water / Total loss of feed water, [7] Emergency core cooling system, [8] Reactor coolant system, [9] Station Black Out

4. Discussion

In the light of current knowledge, it cannot be generally concluded that either analogue or digitalized HSI of the control room would always be better than the other. The usability and ability of the HSI to support error-free actions of the operator depends highly on the specific control room implementation as well as on supporting factors such as training. Not only do analogue and digitalized control rooms differ with regard to the working environment, but also the task composition and level of automation as well as the dynamics and communication of the personnel may be different. The challenge for HRA of ACRs is to capture in an appropriate way the new and partly design specific factors supporting or impeding operator work, in order to be able to give realistic and consistent HEP assessments and compare alternative solutions. When renewing a control room with a digital HSI, the NUREG-0700 guidelines state that the HRA analysts should consider the original assumptions, the set of human errors modelled, the HEPs, new errors and the consequences of errors. In short, this means that all main parts of the HRA may be affected by the change.

As described in Section 2, digitalized HSI has the potential to provide supportive new features such as place-keeping functions to support operator performance when, e.g., the procedure has several parallel paths to follow simultaneously and the operator may lose track of the point reached so far. Digital user interfaces may also provide more information on different screens, compared with the solid analogue panels. The information can be more detailed than in the analogue user interface, about matters not visible at all in the analogue user interface, such as trends, i.e. progression of key process parameters over time possibly even including a forecast. Increased automation may support safety by reducing the possibilities for an operator to make erroneous control over the nuclear process, but may also result in decreased situation awareness and reduced effectiveness of manual checks. However, the digital user interface may repeat the same types of mistakes than the analogue one, e.g. by locating the buttons to push too close to each other. Furthermore, new challenges may arise due to digitalization when, e.g., the increase of information available for the operator is not accompanied with an effective system to find that information. In any case, the new designs usually introduce new interface management tasks which may burden and distract the operator. The well-intentioned new features may be confusing or not very useful and the new working concept affects also the communication and situational awareness of the operators.

Ideally, the effects of these qualitative consequences of digitalization on error probabilities should be assessed quantitatively in empirical experiments and using operational data. As shown in Section 3, some efforts have been made in this regard, but there is still work to be done. The empirical studies show that training and experience, availability and quality of procedures as well as task type or complexity are (still) among the most important PSFs. These aspects are all affected by digitalization in several ways; most of the identified qualitative consequences of digitalization affect these PSFs either directly or indirectly. The impact of the PSFs on HEP values of human actions may potentially also differ from the analogue setting. However, although the information and control systems and their user interfaces differ substantially between analogue and digital control rooms, including the introduction of new secondary tasks, the current studies (see Table 4) do not give much information about their effects on the error rates.

The focus areas, challenges and methods of operator training are likely to be different in ACRs than in analogue control rooms. The HSI is more multifaceted than in analogue control rooms, similar tasks are realized in different ways and new secondary tasks are introduced. Furthermore, digital HSI may be more frequently updated than analogue systems, despite of the conservativeness of the nuclear field.

Digital, on-screen EOPs can differ substantially from paper-based ones. In addition to the obvious differences between working with paper or a screen, the electronic EOPs have both potential for new features supporting the operators' task and possibilities for increased complexity and other deficiencies. The procedure designs are still evolving and empirical studies such as the one by Xu et al. [2008] give valuable information on their safety impacts. Different procedure styles may also be better suited for different tasks.

As already stated, the changes in HSI and level of automation both cause that the same tasks are realized in different ways, but they also change the set of tasks the operator is supposed to perform. Therefore it is important to perform a detailed task analysis to identify the tasks and error possibilities as well as the relevant contextual factors. The study by Andresen et al. [2004] showed that the operators did not like completely automated implementations of procedures due to the resulting deterioration of situational awareness, but were more comfortable with partly automated solutions. More automated operation of the plant would likely prevent human errors, but would probably be insidious in less standard situations where knowledge based decisions are required.

ACRs still being relatively new, only a few empirical studies on the HEPs in ACRs and the associated effects of different PSFs have been carried out, and relevant data from simulator training and operational experience are still scarce. This calls for further quantitative studies both to confirm and clarify the conclusions made and to explore the effects of less studied factors. It is reasonable to assume that simple tasks, such as readings of overview displays, would have similar error rates as the equivalent reading tasks in analogue control rooms, but most task involving e.g. navigation through menus or use of screen-based EOPs with functionalities differing from the paper-based ones, are worth further studies. A few studies on PSFs in ACRs were presented in this paper. However, it is not straight forward to compare or combine their results not only due to their different focus and test settings, but also due to different PSF taxonomies, different task type definitions and different analysis methods, some of which producing interesting numerical results but no assessments of their uncertainty. Thus, the efforts of developing empirically justifiable HRA suited for ACRs would gain considerably from standardized PSF and task type taxonomies as well as an agreement on best practice analysis methods.

Systematic collection of HRA data from simulator training and operational experience is also encouraged. One such effort is the recently introduced HuREX data collection framework in Korea [Jung et al. 2017]. Meta-analyses combining information from several studies and converting their statistics into common metrics could also give further insights on these matters if sufficient amounts of data were available. Tran et al. [2007] propose one such method aimed for assessment of PSFs in HRA. Another example is Griffith and Mahadevan [2015] who combined studies on sleep deprivation from different fields of application and found evidence on increased reaction time and number of lapses after 24h of wakefulness, but no significant effect on task accuracy due to sleep deprivation.

5. Conclusions

This paper reviewed current knowledge about the effect of digital HSI on human behaviour and reliability, relevant standards and guidelines as well as research on the effect of PSFs on HEP estimates in ACRs. It cannot be generally concluded that either analogue or digitalized HSI of the control rooms would be always better than the other. ACRs have the potential to offer error reducing and supportive features to the user, but may also introduce increased complexity and many new interface management tasks as well as potentially error-prone team working practices. The methods of implementation of ACRs are still evolving and their effects on human reliability depend to a large extent on the specific design concept and realization.

The main PSF categories familiar from HRA of traditional control rooms and suggested by standards and guidelines seem relevant also in ACRs. Especially training and experience, availability and quality of procedures as well as task type or complexity are shown to be still important. However, control room digitalization changes the way in which the PSFs should be defined and measured, and their extent of effect on HEP values may be different. In current studies, statistically significant PSFs have been identified using ANOVA and estimates of their quantitative effects on the HEPs have been derived e.g. using logistic regression. This subject would still benefit from further research. Especially tasks involving navigation through menus or use of screen-based EOPs with functionalities differing from the paper-based ones should be focused on. Development and agreement on a common PSF taxonomy and best practice analysis methods would be highly recommendable. As more experience on operational ACRs is gained, analysis of operational data becomes also a viable option. Meta-analyses combining the data from several studies could also have the potential to increase the knowledge base for performing HRA of ACRs, if only sufficient data were available.

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