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Comparison between conventional and digital nuclear power plant main control rooms: A task complexity perspective, part I: Overall results and analysis

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ABSTRACT

Digitalization is a trend in safety-critical complex systems. It changes the way human interacts with systems. We have less empirical knowledge about its potential negative effects on human. In our study, we compared conventional and digital main control rooms (MCRs) in nuclear power plants (NPPs) from a task complexity perspective. Complexity factors in MCRs were quantified in terms of three aspects, frequency of occurrence, complexity induced by their being, and impact caused by them. A total of 69 licensed operators participated in the study. The study consists of two parts. In Part I, overall results and analysis were reported. Generally, operators in digital MCRs perceived higher frequency and higher impact of complexity factors than those in conventional MCRs, no matter in abnormal/emergency or normal situations. Operators in digital MCRs perceived higher complexity than those in conventional MCRs in abnormal/emergency situations. These findings suggest that operators in digital MCRs experience higher complexity and workload which may reduce their reliability. These findings imply that we should caution the side-effects of ubiquitous digitalization in complex industrial systems.

Relevance to industry: Digital technologies are widely deployed in the nuclear industry. They change the working environments in which operators interact with NPP systems. There is insufficient research on operator experience on the changes brought by technological developments in NPP control rooms. Our findings imply that we should take care of the potential negative effect of digitalization on operator working environments.

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1. Introduction

Nuclear power plant (NPP) domain is in the age of digitalization. On the one hand, conventional NPPs are modernizing and upgrading their analogy instrumental & control (I&C) systems in main control rooms (IAEA, 2004). For example, one conventional NPP in our study is planning to replace their paper-based emergency operating procedures (EOPs) by computerized ones. On the other hand, NPPs under construction and about to start construction widely adopt digital I&C systems. Nuclear reactors under construction and planned in China, such as Generation II (e.g., CNP-600), II+ (e.g., CRP-100), and III reactors (e.g., AP1000), etc., feature digital I&C systems (World Nuclear Association, 2013). In modernized or digital NPPs, various advanced human–system interfaces are introduced, such as advanced alarms systems, computerized EOP systems, graphic display systems, and intelligent operator support systems (Roth and O'Hara, 2002). Digital systems are supposed to have many benefits over analog systems in NPPs, for example, improved system performance in terms of accuracy and computational capabilities, higher data handling and storage capacities, and easier to use and more flexible (National Research Council, 1997). Regarding operators, their major role is changed from active controllers to supervisory controllers. In digital main control rooms (MCRs), operators are required to monitor and control digital I&C systems. It is expected that operators' workload, errors, and job requirements are reduced and their situation awareness and accuracy of operations are improved in digital MCRs.

However, digitalization, automation, or computerization is a double-edged sword. It is believed to enhance the safety and productivity of complex systems (Joe et al., 2012). It may also induce unexpected side-effects on operators in the systems due to the poor interaction between operators and the advanced systems. Two terms "clumsy automation" (Wiener, 1989) and "automation

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surprises" (Sarter et al., 1997) have been suggested to describe the potential unexpected effects of automation. The unexpected effects include degradation of operator skills (Bainbridge, 1983), narrower attention or keyhole effects (Woods et al., 1990), higher workload in emergencies (Wiener, 1989), lack of situation awareness (Skjerve and Skraaning, 2004; Gertman et al., 2012), high demands for tracking the behavior of automation systems (Sarter and Woods, 1995), new mode errors (Sarter and Woods, 1995; Sarter, 2008), new knowledge demands for understanding the interaction between the coupled elements of systems (Sarter et al., 1997), secondary interface management complexity (O'Hara et al., 2002), new coordination demands between crew members (Salo et al., 2006) and between human and systems (Sarter et al., 1997), and so on. In the NPP domain, the challenges and threats have been documented in several studies (e.g., National Research Council, 1997; O'Hara et al., 2002; Salo and Savioja, 2006; Zhou et al., 2012; Hickling and Bowie, 2013).

Although the side-effects due to the breakdown in human–automation interaction have been known, we have to note that evidence supporting the side-effects usually comes from simulated studies, accident reports, and operator interview. We have limited empirical evidence, which may be against by the advocates of digital devices who may ignore or underestimate the above listed side-effects. This study systematically compares the differences between conventional MCRs and digital MCRs in NPPs, in terms of a task complexity perspective, to provide empirical evidence on the side-effects induced by digitalization and automation. We focus on two main questions:

(1) Compared with operators in conventional MCRs, do operators in digital MCRs perceive higher complexity?
(2) Compared with complexity factors in conventional MCRs, which complexity factors in digital MCRs change?

Our study consists of two parts. The first part is to answer the first question, which is an overview analysis, and the second part is to answer the second question and to give more diagnostic information, which is a detailed analysis. In the first part, we measured complexity factors in terms of their frequency of occurrence, complexity induced their being, and negative impact placed on MCR tasks. We developed two complexity questionnaires (see the Appendix) corresponding to two situations (abnormal/emergency and normal). The psychometric characteristics of the questionnaires were reported. There were 69 licensed NPP operators with different experience in conventional and digital MCRs completing the two complexity questionnaires. The effects of plant types (conventional vs. digital) and operator experience (junior vs. senior) on complexity factors' frequency, complexity, and impact were analyzed.

2. Methods

2.1. Participants

In total, 69 licensed male operators in the Daya Bay and Ling Ao NPPs participated in this study. MCRs in Daya Bay NPP are conventional (Fig. 1) and in Ling Ao NPP are digital (Fig. 2). In the two plants, licensed operators are classified into five categories (from low to high level of experience): reactor operator (RO), block manager (BM), deputy shift supervisory (DSS), unit supervisor (US), and shift supervisor (SS). According to the suggestion by one NPP operational executive and also for the sake of running statistic analysis, the five categories of operators were re-classified into two bigger categories according to their experience: junior operators (RO, BM, and DSS) and senior operators (US and SS). All participants completed the survey right before or after a work shift. Their demographic information is given in Table 1. In digital MCRs, senior operators usually have about two years working in conventional MCRs and junior operators have less experience in conventional MCRs. The reason lies in the fact that the first-generation operators for digital MCRs mostly came from conventional MCRs after retraining, for speeding up the use of digital systems. The new generation does not have to work in conventional MCRs first. Operators in conventional MCRs may have some but less experience in digital MCRs.

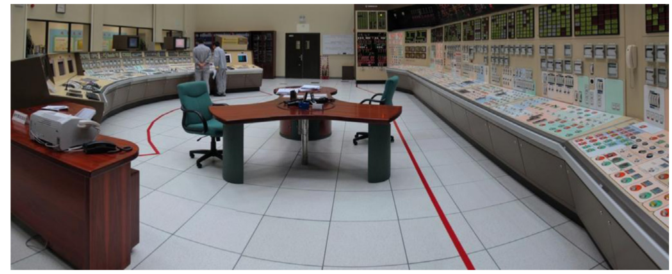

Fig. 1. Daya Bay full scope simulator (Source: Daya Bay NPP).

Fig. 2. Ling-Ao Phase II full scope simulator (Source: Ling-Ao NPP).

2.2. Complexity questionnaire design

2.2.1. Quantifying complexity factors

The way to quantify complexity factors in MCRs is critical in our study. Researchers in OECD Halden Reactor Project (Braarud, 1998, 2000; Collier, 1998) used a Likert type scale and required

Table 1
Demographic information of participants.

	Conventional MCRs ($n = 27$)		Digital MCRs ($n = 42$)	
	Junior ($n = 19$)	Senior ($n = 8$)	Junior ($n = 32$)	Senior ($n = 10$)
Age	29.80 (1.57)	35.53 (2.94)	30.51 (2.24)	34.33 (2.60)
Yeas being licensed	2.16 (1.37)	9.19 (3.21)	2.36 (1.14)	6.43 (2.47)
Yeas working in conventional MCRs	2.39 (1.45)	7.63 (3.46)	0.28 (0.89)	2.25 (1.62)
Yeas working in digital MCRs	0.05 (0.23)	0.00 (NA)	2.58 (1.18)	3.60 (1.51)
Yeas working in MCRs	2.45 (1.56)	7.63 (3.46)	2.86 (1.82)	5.85 (2.38)

Descriptive means are outside () and standard deviations are in ().

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