Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26422-cd

Do individual differences matter in technologically advanced control rooms?

Prosper A. Kwei-Narh

Human & Organizational Factors Department, Nuclear Division. Institute for Energy Technology, Norway.

E-mail: prosper.kwei-narh@ife.no

Kine Reegård

Human & Organizational Factors Department, Nuclear Division. Institute for Energy Technology, Norway.

E-mail: kine.reegard@ife.no

Jan Ketil Arnulf

Department of Leadership & Organizational Management, BI Norwegian Business School, Norway.

E-mail: jan.k.arnulf@bi.no

Technologically advanced control rooms (advanced control rooms) automate tasks, reducing human intervention and enabling operators to offload cognitive work. Theoretically, this creates a high situational strength through situational clarity and consistency, reducing variance in operator idiosyncratic behavior. Yet prior research shows that individual differences continue to shape operators' performance, raising questions about how human variability interacts with the affordances of the advanced control room. Given the increasing automation and digitalization of control rooms, there is a renewed need to understand the human-factors dimensions of operator experience, particularly how individual differences influence control room performance. A critical realist analytic framework was used to analyse data from semi-structured interviews with nine licensed U.S. nuclear power plant operators after their participation in simulations. We identify underlying mechanisms that link operators' experiences to deeper structural and psychological factors. Our findings indicate that advanced control rooms contain the well-known demands of traditional control rooms. In addition, they require control room operators to rely on their individual pattern recognition abilities, handle emergent risks embedded in the 'black box' automated systems, and shift roles. Changes in staffing models further alter teamwork demands, underscoring the need for self-regulation at the individual and team levels in stressful situations. These insights reveal that although advanced control rooms function as strong situations, they also contain grey situations, moments in which individual differences meaningfully shape outcomes. Recognizing these interactions is essential for designing interfaces that better support human cognition, developing training that prepares operators for uncertainty, and updating analysis methods to reflect the realities of work in advanced control rooms.

Keywords: Human-technology interaction, Human performance, Individual differences factor, technologically advanced control room, nuclear power plants

1. Introduction

Technologically advanced control rooms in the nuclear industry mark a significant shift in sociotechnical system design. New interfaces offer more integrated, system-level information, often combining multiple sensor readings and alarms on a single display (Chen et al., 2017; Wu et al., 2016). Simultaneously, the increasing automation in the control rooms is moving operators from active monitoring to supervisory roles (Boring, 2023). Regulatory guidance for advanced control rooms, for example, continues to emphasize workload management, situational awareness, and human–machine interface design (O'Hara et al., 2012). By design, nuclear control rooms are strong situations, that is, work environments in which well-defined procedures, structured roles, and consistent operational cues constrain behavioral variability (Meyer et al., 2010). In strong situations, the influence of individual differences (e.g., personality, cognitive style) is reduced (Judge & Zapata, 2015). However, advanced control rooms introduce complexities that may weaken these constraints, raising questions such as how individual differences manifest and interact with new features. We explore these questions using theory and semi-structured interviews with licensed operators. Our paper highlights how variability in information-processing styles, decision-making, and teamwork skills interacts with advanced control room affordances as boundary conditions for operator effectiveness in the advanced control room. This can enrich human factors considerations for control room experience and inform regulatory practices (O'Hara et al., 2012).

2. Background and Theory

2.1 Situational strength theory

Situational strength theory offers a useful lens for explaining the human-advanced control room interaction. It proposes that every situation varies in whether they contain "implicit or explicit cues provided by external entities regarding the desirability of potential behaviors" (Meyer et al., 2010, p. 122). Although there are four dimensions of these situational strength variations (i.e., clarity, consistency, constraints, consequences; Meyer et al., 2010), we will focus on clarity and consistency.

Clarity of a situation reflects "the extent to which cues regarding work-related responsibilities or requirements are available or easy to understand" (Meyer et al., 2010, p. 125), rules for what is expected behavior are not ambiguous and applies for everyone. The second dimension of situational strength we consider relevant is *consistency,* reflecting "the extent to which cues regarding work-related responsibilities or requirements are compatible with each other" (Meyer et al., 2010, p. 126).

Applied to our context, traditional nuclear control rooms exhibit strong situational strength through detailed procedures, prescriptive role structures, and clear information flows limiting individual variability (Judge & Zapata, 2015). Yet advanced control rooms may diffuse the strength and experience of the situational strength of control room because they contain scenarios where operators must adapt without necessarily having the explicit routines in place and where situational cues become less constraining.

For instance, novel interface designs or multi-unit supervisory tasks could reduce clarity or introduce conflicting cues, giving more latitude for an operator's traits and abilities to affect performance. This shift presents new conceptual and empirical challenges for predicting and supporting operator performance under these conditions. In this paper, operator performance refers to the achievement of work objectives (such as safe and efficient plant operation) that emerge from an interplay of individual capabilities, work structures, and technological affordances.

2.2 Individual differences in the control room

Control room work inherently demands intensive information processing, complex decision-making, and team coordination (O'Hara et al., 2012). These cognitive and social processes are influenced by individual differences (Zhang et al., 2013). For example, operators who score high in extraversion (and related traits like gregariousness) tend to perform better in the control room (Xiang et al., 2008); conscientious operators are better at identifying and diagnosing faults (Kim et al., 2020), and proactivity in taking decisions under uncertainty are essential to control room performance (Xiang et al., 2008). Individuals vary in teamwork-oriented competencies such as emotional stability and communication style (Skjerve et al., 2013). These attributes influence situational awareness, diagnostic reasoning, risk perception, and interpersonal coordination. These findings illustrate that personal characteristics can shape important aspects of control room work performance.

The information-processing requirements in the advanced control room mean greater demands on cognitive abilities. Cognitive ability (for example attention, memory span, problem solving, and pattern recognition) has historically been one of the strongest predictors of job performance across many domains (Sackett et al., 2022), including success on operator licensing exams and with safer operator performance (Zhang et al., 2013). However, malleability and range restrictions are caveats to consider when evaluating such individual differences in cognitive abilities in the advanced control rooms.

First, targeted practice or environmental changes makes cognitive abilities malleable (Nisbett et al., 2012). This means that an operator's test scores might not fully capture their potential or growth trajectory, especially if advanced control rooms demand new cognitive strategies that can be learned over time.

Second, training and uniform education will likely minimize cognitive ability variance among operators. This means the predictive validity of cognitive abilities on performance will be minimized due to "restriction of range" (Van Iddekinge et al., 2026). This measurement challenge, along with the complex manifestation of cognitive abilities in the real world, means we must pay attention to the context in which these abilities are likely to be impactful.

Additionally, high-performance teams often establish norms that boost overall outcomes. For example, the habits and expectations set by top performers on a team can greatly raise others' performance. In future control rooms, we should expect that fostering the right team dynamics and learning culture could offset some weaknesses or strengthen the advantages of individual differences (Woolley et al., 2015).

3. *Method*

3.1 Participants

Nine licensed U.S. nuclear operators, reactor operators, senior reactor operators, shift supervisors, and a technical director, participated; experience in the control room ranged from 2 to 25 years.

3.2 Data collection

The main data collection was semi-structured interviews. The interviews were conducted after the operators participated in scenarios in two simulated environments so that they would have concrete experiences with certain aspects of advanced control rooms such as new teamwork structures, digital controls and information displays, automation, and computerized procedures.

Participants took part in simulated scenarios in two advanced simulator environments: (i) the HAMMLAB full-scope iPWR with a six-unit configuration mimicking a multi-unit concept operated by a three-person team, and (ii) the HAMMSAT, a single-unit nuclear power plant mimicking a single-person operational concept. Both environments included integrated process displays, multi-unit alarm systems, and digital procedures (for details, see Blackett et al., 2023).

The scenarios were developed by colleagues at IFE for other scientific purposes. Each scenario began with a shift handover. Participants received briefings on unit status, planned maintenance, and load adjustment instructions. Scenarios lasted approximately 35 minutes and followed a predefined schedule of malfunctions and events, including instrument failures, component malfunctions, safety system activations, and reactor trips. During the scenarios, participants could communicate with field operators and maintenance staff, role-played by a subject matter expert (SME) in the observation gallery.

Each interview lasted approximately one hour. Interview topics included operators' perceptions and experiences in the simulated environments, challenges encountered, responses to digitalized procedures, and reflections on control and job engagement. This method let participants share their experiences, thus helping authors identify causal mechanisms for participants' experience. Interviews were recorded, transcribed, and anonymized. Transcripts were imported into NVivo 15 (QSR, 2025) for coding and analysis.

3.3 Analytical approach

The analysis was guided by a critical realist approach which views reality as layered into three ontological levels: the empirical (experiences and perceptions), the actual (events that happen, whether observed or not), and the real (the underlying causal mechanisms behind events). We combined thematic analysis with theory-building. We used Fryer's (2022) five-step framework to develop causal explanations for the operators' experiences. We examined the data considering participants' expressions, connected those responses to existing theory, and sought to explain participants' experience by relying on psychological structures and situational clarity and consistency. We applied retroduction to infer plausible causal mechanisms underlying the identified themes

(Lawani, 2020), asking what structural, technological, or individual-level conditions must exist for the observed experiences to occur. The research team drew on domain knowledge and relevant human factors literature to theorize about the causal mechanisms.

4. Findings & critical realist interpretations

The interviews revealed interrelated themes about operators' experiences in the advanced control room (empirical) interpreted in the light of underlying causal mechanisms (actual and real domains).

4.1 Information Processing and Cognitive Load

Operators characterized the advanced control room as information-rich, imposing heavy demands on attention and cognitive flexibility. Some reported a monitoring threshold: "three is my limit, beyond that I'll miss things" (P4). Others noted that "some operators can only do one thing at a time… those operators would not be successful operating multiple units" (P1). To cope, they leaned on pattern recognition; noting that operators "have a very good ability to do pattern recognition," often "instead of gathering all the data, they gather two data points… and then act" (P6). *Interpretation*: These accounts indicate that the advanced control room provides rich information but also poses demands on attention and working memory (Fernandes & Braarud, 2015). Wide-screen displays and integrated alarms streamline access to information, increasing *situational clarity*, yet cognitive saturation remains a structural constraint in these advanced control rooms, challenging *situational clarity*. Operators noted there are practical limits for how many units they can monitor. In dealing with work demands, they rely on pattern recognition and rapid scanning. Reliance on pattern recognition is an adaptive shortcut that enables timely action but risks missing subtler cues and getting back into the 'loop' during operator takeover of tasks.

4.2 Decision-Making and Risk Perception

Decision styles diverged. Some preferred "throw me at a problem, let me fix it, and then let it go away" (P6) while others referred several times to "check", "peer check" saying that is "…logic and the standard of why you as an operator want somebody actually checking you… because one mistake then you could suffer financially or you could lose your qualifications" (P9). Operators recognized new risk sources captured by statements such as "more technology means more things that can break" (P5). Risks were sometimes embedded in emergent tasks or in unclear conditions. As one informant observed "in general if you understand what's automated and what's not you can be prepared to accommodate" (P8). Multi-unit oversight added the hazard of acting on the wrong interface; " It's easy to get on the wrong unit because it's not physically…" (P9), highlighting the need for vigilance and engineered distinction in the unit display systems in the advanced control room. A dilemma was how to prioritize events: "If there's a third unit that trips… we'd have to prioritize… I'm supposed to stay with this one because it's got a red alarm… but I might be able to prevent [another unit] from tripping… so you have to make those decisions" (P9). The advanced control room will impact their sense of control, where "being in control means understanding your current situation and your path forward" (P2). Role switching (e.g., a supervisor performing an operator's task) was highlighted as a significant error precursor and a source of stress (P8). *Interpretation*: Where there are abnormalities or fault conditions, novel, concurrent, or ambiguous events, existing procedures may provide less guidance, and individual propensities (risk tolerance, confidence, mental models, trust in automation) may drive choices (e.g., Xiang et al., 2008). This points to loosening *situational consistency*. System complexity increases the risk of confusion (e.g., actions on the wrong unit). The need to prioritize simultaneous events highlights a fundamental constraint of the actual environment (the advanced control room). Any operator can address only one problem at a time, potentially leaving adjacent units vulnerable to fault propagation. Thus, a causal mechanism at play is the need to prioritize under stress, which can lead to suboptimal outcomes for whichever action/unit is deprioritized (minimized *situational consistency and clarity*). Moreover, operators' emphasis on understanding the situation as key to feeling in control underscores that situational awareness is a causal mechanism for effective decision-making. When situational awareness depletes (due to overload or opaque process logic), operators feel “out of control,” which can precipitate conservative decisions or, conversely, risky guesses (minimized *situational consistency and clarity*). The meaning of control, though, varies according to the role of our interviewees (RO, SS..).

4.3 Teamwork and Social Support

Teamwork was both protective and burdensome. Many valued the support available when being part of a crew in the control room, having “a backup set of eyes” (P7) and felt uneasy about single-operator concepts as “being the only one, with no backup, adds stress” (P9). A similar concern arose with multi-unit operations, where participants found that losing that verification step as their work became more fragmented was “the most stressful part” of monitoring multiple units (P8). Yet collaboration could slow action, as captured by one participant: “too many opinions delay decisions” (P5). Continuous teamwork coordination also raised perceived workload. Yet, operators varied in their preferences for teamwork: some sought peer verification and open challenge as “critical safety aspects,” while others preferred autonomy and found excessive collaboration to be “noise.”
Interpretation: In traditional control room crews, teamwork aspects such as information sharing, cross-verification, and role allocation facilitate the shared mental models necessary for adaptive performance (increasing *situational clarity and consistency*). These structural safeguards are lost when crews are absent, (changing *situational clarity*), shifting the burden to individual cognition and self-regulation. Conversely, coordination can also be costly under time pressure. Therefore, the potential successes of the new crew configurations will depend on access to technological substitutes and decision support systems (Hsieh et al., 2012). Increased work demands can also arise from being solely responsible for emergent risks.

4.4 Situational Strength in the technologically advanced control room

Finally, the advanced control room continues to adhere to, while diverging from, the established protocols of traditional control rooms. Many aspects of the job remain highly prescribed and constrained (strong *situational clarity and consistency*). That means routines, roles, and procedures remain strong (Judge & Zapata, 2015). Shifts begin with “a plan of the day… you methodically work through that plan, going through the procedures and the surveillances” (P1), and “roles and responsibilities are pretty well defined.” This clarity supports task allocation and handovers, contributing to situational strength. Yet multi-unit designs introduce ambiguity despite adequate procedures. The risk of operating the wrong unit persists despite safeguards, especially under abnormal load. Some risks are identified: “most risky tasks being the emergent ones, right, the ones that weren't planned…an alarm comes in, unexpected equipment failure occurs, they have to respond in the moment” (P8). Emergent and novel failures require improvisation and role-switching. These departures from traditional roles during shifts dilute situational strength. Having said that, some operators seemed to adapt quickly, drawing on their experience and previous training (e.g., P.5), but also finding similarities between the simulation to a video game, saying: “the acclimation to this was quick…honestly, it's kind of like a video game” (P2).
Interpretation: Advanced control rooms contain aspects of both strong and weak situations. Formal structure usually dominates, masking individual differences during routine work. But failures during multi-unit operation, opaque automation, or compound alarms create grey situations where cognitive heuristics, risk aversion/propensities, experience and communication style may be very impactful. Performance thus reflects an interaction between enduring structural constraints of the advanced control room and dynamic, individual factors. Recognizing these grey situations in the advanced control room can facilitate targeted support. Some of these involve the use of standard human factor interventions, such as clearer multi-unit differentiation and adaptive procedures for compound events.

5. Discussion

This study examined how individual differences reflected by cognitive aspects, decision-making, risk perceptions, teamwork, and social support will be important in advanced control rooms. Our findings indicate that individual differences in these aspects are important for understanding how individual characteristics interact with the situational strength of the control room to influence operator experiences and performance. By combining situational strength theory with critical realist analysis of operators' experiences, we identified mechanisms that explain how advanced control rooms enable individual differences to have a significant impact.

Beyond the explanatory mechanisms we advanced above, some core findings can potentially impact our understanding of work demands in advanced control rooms. While we focus a lot on the individual differences related to cognitive abilities and their potential interactive effects on control room performance, prevailing familiarity will also affect operator's experience of workload, so the more experienced operators find high-task-load periods less stressful than those who are relatively inexperienced. In fact, experienced operators reported being most engaged during high-task load periods (Drøivoldsmo et al., 2025). Personality traits such as introversion were also mentioned as explanations for how the operators experienced social interactions that either detracted from or replenished their energy in the control room. These observations matter when designing work in advanced control rooms (O'Hara et al., 2012). Differences in experience can be important to balanced team composition. This will ensure there is an adequate repository of tacit knowledge to facilitate pattern recognition needed for diagnosing problems during failure scenarios or in high-demand situations. Personality traits can also be important to consider when setting up teams to distribute team competencies for effective teamwork (Skjerve & Holmgren, 2018). When selecting personnel for single-operator control rooms, consider personality types, cognitive flexibility, and field dependence to maintain situation awareness necessary to address emergent risks during failure scenarios. Finally, advanced control rooms and their new operations may increase the importance of operators' self-awareness of their capabilities and limitations as the complexity of the situations they handle increases. Indeed, "the ability to recognize when they're running out of bandwidth to effectively and safely operate the plant" was emphasized by one operator as a core skill in single-operator settings.

A central insight is that advanced control rooms do not uniformly strengthen or weaken situational cues; rather, they reconfigure the distribution of situational strength across tasks and scenarios. During routine operations, the control room continues to function as a strong situation (Judge & Zapata, 2015), and behavior follows the predictable scripts and roles as in any traditional nuclear power control room. Thus, individual differences remain largely masked. This does not mean that the traditional control room is immune to the effect of individual differences, rather they are expressed in limited ways.

However, advanced technology may introduce moments when clarity and consistency of cues are reduced, and individual judgment, risk assessment, proactivity, and self-regulation become consequential. These effects can be traced to the following. First, information-rich, multi-unit monitoring exposed cognitive saturation limits, forcing operators to rely on attentional shortcuts and pattern recognition. While such heuristics enable timely action, they also force variation in cognitive strategies, tolerance for ambiguity, and susceptibility to missed cues. Second, unexpected or unknown system behaviors and ambiguous technological aspects (such as errors in a system rather than a component) will affect operators differently. Those with experience or who can engage in calculated risk assessments are more likely to handle these demands effectively. These findings underscore how automation can create new failure modes that amplify rather than suppress individual differences.

Third, proposed changes in control room staffing configurations, which will influence the number of team members and team interactions, highlight that situational strength is also social. Having a crew member as a sounding board, providing another pair of eyes to the data, helps operators to work securely in the control room. When these mechanisms are weakened, whether through single-operator concepts or increased coordination complexity, individual differences in personality aspects and proactivity will be very important, as will a flexible mix of conservative and risk-informed decision-making. The demands for shared mental models necessary for adaptive teamwork will change. In a traditional stable crew configuration, shared mental models emerge through team interactions, thereby facilitating adaptive teamwork. In advanced control rooms and multi-unit configurations, shared mental models will be needed when crew roles must switch within a task on one unit to handle an emergent issue in another unit. We consider this important, as the shared mental model is important for adaptive performance in the control room.

Work performance in technologically advanced control rooms increasingly depends on how operators use the integrated displays, automation, and digital procedures to support attention and decision-making. This cognitive offloading has its critiques (Kosmyna et al., 2025), yet our findings suggest that offloading is not inherently harmful but becomes essential for managing multi-unit complexity and high information load (Mitchell & Krakauer, 2023). In these situations, differences in pattern recognition, situational awareness, and risk perception shape both the use of advanced technologies and the nature of the cognitive offloading.

Taken together, these findings suggest that operator performance in advanced control rooms arises from a dynamic interaction between operators and their situations rather than from deterministic influences of technology or procedures. The control room remains fundamentally structured, yet the integration of advanced technology and new teamwork structures introduces novel conditions in which individual capabilities, dispositions, and strategies meaningfully shape outcomes. Situational strength becomes unevenly distributed across the work system: strong during routine, proceduralized activity, and weaker during multi-unit disturbances, ambiguous automation behavior, or novel system-level events.

This nuanced understanding has several implications. For designers, it highlights the need to support operators specifically in weak-situation contexts through clearer interface differentiation, more transparent automation logic, and adaptive procedures for compound events. For training programs, it suggests a shift beyond procedural compliance toward metacognitive skills, uncertainty management, and self-regulation under cognitive load. For human reliability analysis, it underscores the importance of modelling context-dependent operator performance variation rather than assuming uniform operator behavior. Finally, for regulators, these insights reinforce the need to account for individual-difference variability when evaluating advanced control room designs, staffing models, and human–system integration strategies. The study is limited in its claims and findings by the small sample size and lack of direct measurements of psychological attributes.

Acknowledgement

The authors thank Maren Eitrheim, Gyrd Skraaning Jr., Daniel Odéen and Robert McDonald at IFE for collaboration on data collection, the OECD-NEA HTO Project, and anonymous reviewers from the Halden HTO Programme Review Group and ESREL2026 Conference Committee.

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