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A SEM-based research on influencing factors of team situation awareness in nuclear power plants

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Team situation awareness (TSA) is one of the key factors that affect team decision-making and implementation. TSA is influenced by performance shaping factors (PSFs) in digital nuclear power plants (NPPs). In order to identify the influencing relationships and extent between TSA and PSFs, a model is needed to describe and correlate them. Firstly, based on TSA cognitive process, the main PSFs influencing the level of TSA are identified, including team knowledge and experience level, information display quality, attention and attitude, and team stress level. Then a conceptual model of TSA influencing factors is proposed to explore the path relationships and influencing mechanism between TSA and PSFs, and a structural equation model (SEM) that relates TSA to its PSFs is developed subsequently. Finally, by analyzing human factor events and small deviation reports, data from 178 samples were obtained and substituted into the structural equation model to analyze and identify the relationships between the PSFs. The results show that the preceding PSFs have significant effects on TSA. Based on path coefficients, positive effects were: team knowledge and experience level (0.504), information display quality (0.370), attention and attitude (0.249). Negative effect was: team stress level (−0.384). The results of this study can provide a theoretical basis for the prevention and control of TSA errors, and a qualitative analysis model for the quantitative evaluation of TSA reliability.

KEYWORDS
team situation awareness (TSA), structural equation modeling, performance shaping factor (PSF), influencing relationships, digital nuclear power plants

Introduction

The application of digital control technology improves the reliability of hardware and software, even enhances the overall performance of the system. However, due to the numerous uncertain factors of human, including physical, psychological, social and spiritual factors, human show great plasticity and uncontrollability, and human error is the key cause that triggers accidents (Zhang, 1998). Human error accounts for a large and growing proportion of accidents. Statistically, over 78% of accidents in NPPs are associated with human error (Li et al., 2020). Nearly 75% of aviation accidents were caused by pilot error (Kelly and Efthymiou, 2019). The majority of human error is caused by operator's situation awareness (SA) error. According to Endsley (Endsley, 1994), 88% of all aviation accidents caused by human error could be attributed to SA error. Moreover, in a complex dynamic system such as a NPP, most tasks are completed by team members. Team members, who have been assigned specific roles involving different functions of limited time durations, interact toward a common goal or objective. The role of each team member may have associated with a subgoal that is supportive of the overall team goal, the completion of different sub-goals requires different SA elements. SA elements that allow the operator to fulfill his or her own team responsibilities and that other team members do not normally own are the components of team situation awareness (TSA). The extent to which each team member has SA on these SA elements for task performance is the TSA (Endsley, 1995). Therefore, team situation awareness (TSA) is the sum of the SA for each individual, independent of any overlap in SA requirements among operators (Kaber and Endsley, 1998). In such a complex system with high safety sensitivity like nuclear power plant, TSA is particularly important. Whether the monitoring and detection of system under normal states or response to abnormal conditions, it is all coordinated by team members (Li et al., 2017a). Furthermore, a feature of team tasks is that the safe completion depends more on the performance of the team than individuals (Banbury and Tremblay, 2004). Previous studies have shown that TSA is positively correlated with team performance (Lin et al., 2010; Kim et al., 2010). If the team has formed and maintained a high level of TSA, although an individual has made SA error, the error may be discovered, corrected and even recovered by other members (Li et al., 2019). Conversely, a low level of TSA is likely to reduce performance and leads to mission failure. An incident investigation funded by the Abnormal Situation Management Consortium found that most incidents were related to TSA errors (50%) (Bullemer and Reising, 2013). Thus, TSA is crucial for the successful execution of team tasks, and a key element that affect team performance and even relate to catastrophic accidents.

Due to the complexity of system, the various team processes involved in the development and maintenance of TSA (e.g. communication, co-ordination etc) and the various factors affecting team SA level, it is difficult to analyze the construct and cognitive mechanism of TSA correctly, which leads to the lack of systematic research on mechanism of TSA error, especially on the relationship between performance shaping factors (PSFs) and TSA error. In the field of influencing mechanism of TSA, Salas et al. (2006) proposed a conceptual model of TSA, considering that individual SA can be updated and shared through interaction processes such as communication and collaboration among team members, and then TSA can be formed. Although the model discusses in detail the internal components of TSA and the dynamic interactions between each component, it does not explore the influencing factors of TSA and their influencing relationships on TSA. In order to develop an evaluation method of TSA, Nonose et al. (2010) constructed a team cognitive model based on mutual belief. The proposed model is composed of three layers of mental components which represent the structure of mutual belief in team cognition. The first layer represents an individual cognition except beliefs, the second layer represents a belief in the partner's cognition, and the third layer represents a belief in the partner's belief. However, it is not sufficient to describe the error classification and mechanism of TSA from the mutual belief alone. Based on a synthesis of the literature about individual SA and TSA, Salmon et al. (2007) proposed a model that fully describes the processes involved, the contents of TSA and also the factors impacting TSA. According to this model, SA-related data and knowledge is distributed around the team through team processes such as communication, coordination and collaboration, and serves to inform and modify individual SA, which is also informed and modified by the TSA. Although the model elaborates on the components of TSA and their interactions, there is a lack of research on the classification of TSA error and influencing factors of TSA as well as their influencing relationship. Despite the contribution of the above literature to the theoretical study of TSA influence mechanisms, there exists problems that cannot be ignored. The aim of this study is to explore these issues, focusing on identifying major, potential PSFs affecting TSA, the influencing relationship between TSA and PSFs and their degree of influence, and to assess which factor has the greatest effect on TSA.

This paper adopts SEM as a method for constructing the pathways and mechanisms of effect of PSFs on TSA. TSA is influenced by many factors. The factors that affect operators' behavior in work environment are called PSFs. While PSFs have been widely studied, most analysis have only focused on one factor or a small group of factors from a quantitative perspective of experiment. It cannot fully and effectively explain the overall characteristics of TSA in a dynamic and changeable environment. Besides, The PSFs of TSA such as attitude and stress are abstract concept, making direct and effective measurement difficult. Fortunately, quantitative data may be indirectly derived through multiple and measurable indicators. The structural equation model (SEM) provides a means for measuring the relationship between multiple variables at the same time. SEM is mainly used to analyze and identify the relationship between multiple latent variables. Therefore, the method can be used to discern the influencing relationship between these PSFs and their influence on TSA.

Based on the existing research on TSA error (Lin et al., 2010), this study identified main PSFs that induce TSA error, obtained data by analyzing the human factor events and small deviation reports in digital NPPs, and explored the influencing relationship between PSFs and TSA error through SEM. The second section presents the theoretical foundations of this research and the factors that affect TSA. In the third section, the structural

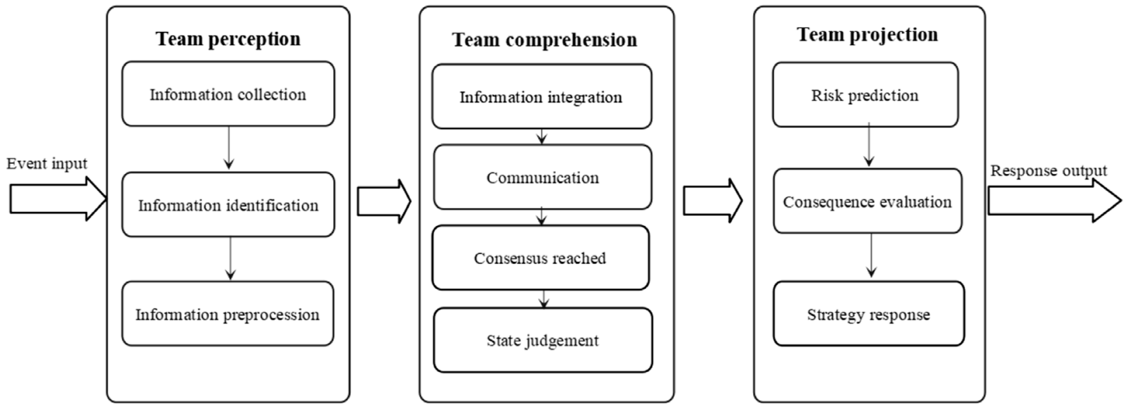

FIGURE 1
TSA level and the cognitive process.

equation model is constructed and data is collected and processed through human factor events and small deviation reports. The results of model validation are addressed in the fourth section followed by discussion in the fifth section, and the conclusion is in the sixth section.

Theory and hypothesis

Over three decades of development of situation awareness theory, a number of theoretical models and research approaches have been developed, such as the information processing model (Endsley, 1995), the perceptual/action loop orientation (Smith and Hancock, 1995). Of these, Endsley's definition of situation awareness is the most widely accepted. Endsley defined situation awareness as the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future. She also divided situation awareness into three levels, the first level being perception in the environment, which is the most basic aspect of situation awareness. The second level is comprehension of the current situation, which is the integration of different information and decisions-making about goals. People at the second level receive important information from subjective and objective sources that are relevant to the operation from the cues obtained at the first level. The third level is projection, i.e. the ability to anticipate future situational events, and is the highest level of situation awareness. TSA encompasses the individual situation awareness, and therefore the TSA also encompasses the above three levels. However, when processing and exchanging information, each team member, influenced by his or her own knowledge and experience, does not quickly or smoothly form a consensus with the other, and it needs to eliminate divergences among the members through the process of team communication, team collaboration and team consensus (this process usually occurs in the comprehension level). As a result, the cognitive process of TSA is more complex and diverse, and more difficult to identify the main factors affecting TSA. Based on the following TSA cognitive process shown in Figure 1, we make the following hypotheses about the main PSFs influencing TSA, which are tested in subsequent sections.

The first step in developing the SEM was to identify the factors that influence TSA. Due to the complexity of the process of developing TSA, TSA in NPPs could be affected by many factors. At present, the most influential factors relative to TSA that have been comprehensively discussed from information display quality, team knowledge and experience level, team stress level, as well as attention and attitude (Li et al., 2019; Li et al., 2017b). Each factor is discussed in turn below.

For the operating team in digital main control room (MCR) of NPPs, when an abnormal event occurs, the team needs to collect and analyze information in order to identify what happened to the NPP and what state the system is in, as well as to verify and evaluate this state (Li Pengcheng et al., 2017; 2018a). In the process of conducting such cognitive activities to form TSA, the team needs to collect a lot of information on the current situation from display screen. Information display quality affecting TSA mainly includes quality of procedure (such as availability and completeness), technical system (level of automation, reliability et al.), and human-computer interface (accuracy and identification et al.) (Lin et al., 2016; Li et al., 2017b; Sebok, 2000; Kaber and Endsley, 2004), all of which help the team to maintain a high level of TSA.

In addition, team stress level may also be influenced by information display quality. Many dynamic system have high complexity and rate of change, requiring operators to focus on information from multiple sources or perform multiple tasks. However, if the system has the functions of guiding attention, integrating data, collecting and disseminating high-quality information, it will reduce the complexity of tasks and relieve the stress on the operator. The following hypotheses are suggested based on the above mentioned discussion:

-H1a: Information display quality is positively related to TSA.
-H1b: Information display quality is positively related to team stress level.

After obtaining the information, the acquisition and maintenance of TSA requires the team to understand and evaluate the information, which is influenced by knowledge and experience. Team members with high level of knowledge and experience can quickly and selectively identify the most critical elements in the environment, and in the form of mental models to integrate the elements to aid understanding of their meaning and prediction of possible future states and events (Lee et al., 2004; Salmon et al., 2008). The knowledge and experience level of team is mainly manifested in experience and training. In addition, team members complete tasks through collaboration, and communication is also an important way to obtain information and knowledge. The adequacy and accuracy of communication is also a reflection of the level of knowledge and experience of team, which can affect the level of TSA (Carvalho et al., 2007; O'Connor et al., 2008; Parush et al., 2011; Shuang et al., 2016). All of these factors can reflect the comprehensiveness and complementarity of the knowledge and experience of team.

Moreover, team knowledge and experience level may have an impact on team stress level. Studies have shown that operators with more knowledge and experience can faster and easier to integrate information and build the correct mental model (John et al., 2002). They will also adopt some strategies to proactively anticipate potential problems or risks, develop contingency plans, and prioritize tasks, so that they can cope with vague, dynamic conditions and time stress. Based on the above discussion, we suggest the following hypotheses:

-H2a: Team knowledge and experience level is positively related to TSA.
-H2b: Team knowledge and experience level is positively related to team stress level.

There have been many researches on the impact of stress on the team cognitive behavior such as TSA (Burke et al., 2008; Li et al., 2017b). As the level of digitization increases, the system becomes more complex due to more information display on limited screen and complex system structure *etc*. In this context, the tasks to be completed by team are characterized by high difficulty and complexity. And tasks under abnormal conditions are often accompanied by time stress and higher accident severity. All these will increase the stress of the team. Higher stress can make individuals tend to narrow the scope of attention and focus on only a few information, which will cause some important information to be ignored, which is not conducive to maintaining a high level of TSA. Therefore, we propose the following hypothesis:

-H3: Team stress level is negatively related to TSA.

The analysis of human error event reports show that attention and attitude are important factors that affect TSA (Li et al., 2018b). Attention is affected by the work environment, such as noise, lighting and disturbance from other personnel. In addition, attention and attitude are mainly determined by the safety culture and work supervision in NPPs. Good safety culture and strict work supervision enable operators to pay attention to safety standards and rules when performing tasks, maintain a good safety attitude at all times, and actively take relevant safety measures. Therefore, the following hypothesis is suggested:

-H4: Attention and attitude is positively related to TSA.

The main purpose of above is to indicate that TSA is influenced by many factors and to describe the relationships between these factors. According to the SEM tactic, from the above analysis and the panel discussion, a conceptual model of influencing factors of TSA is developed as shown in Figure 2. The model is mainly focused on team knowledge and experience level, information display quality, attention and attitude, team stress level that are main influencing factors impacting TSA.

Research model and data collection

The hypothetical structure shown in Figure 2 contains team knowledge and experience level, information display quality, attention and attitude, team stress level that that impacting TSA, which presents the challenge of effectively and directly measuring an abstract and complex concept. However, quantitative data may be indirectly derived through multiple, measurable indicators. SEM as a effective means to measure the relationship between multiple variables at the same time, being mainly used to analyze and identify the relationship between multiple latent variables. Therefore, SEM can be used to explore the relationship between these factors and their influence on TSA.

To identify the main PSFs impacting TSA, we collected 212 incident reports and small deviation reports from 2010 to 2017 in digital NPPs. Of these, 178 (84%) involved human error, while the rest were related to equipment failure or technical failure. The Situational Awareness Global Assessment Technology (SAGAT) developed by Endsley (2002) collects data from three levels of information perception, information comprehension, and information projection to measure the level

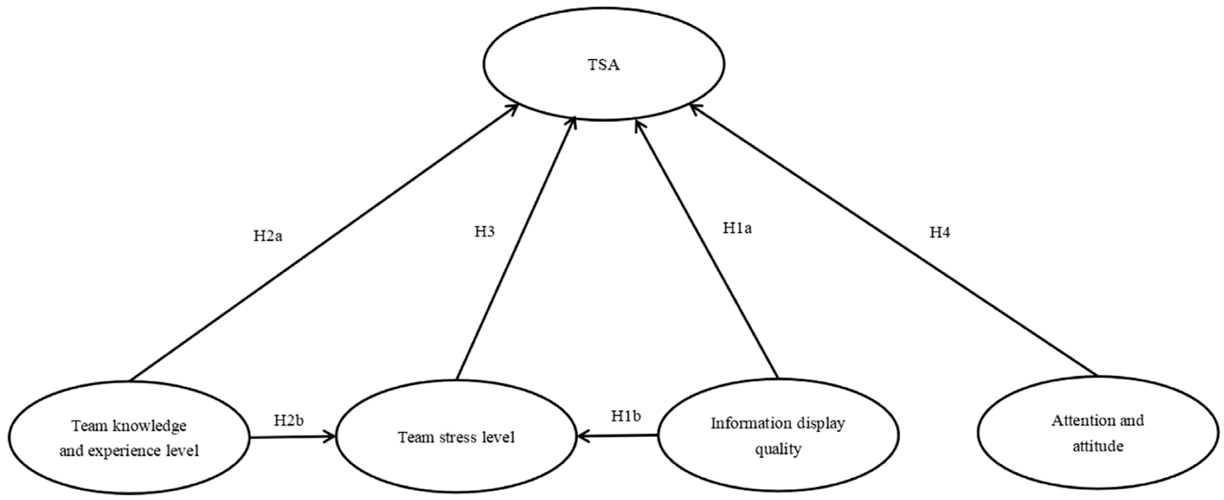

FIGURE 2
A conceptual model of influencing factors of TSA.

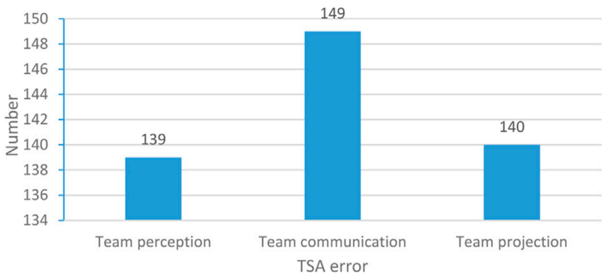

FIGURE 3
TSA error statistics.

of operators' acquisition and integration of task information. SAGAT has been proved to have a high degree of reliability (Yang and Zhang, 2004), to possess sensitivity to condition manipulations (Endsley, 2000), and to be effective across a variety of domains, including air traffic control, infantry operations, commercial aviation and teleoperations. According to Jones and Kaber (Jones and Kaber, 2004), the method is a valid metric of SA.

Using relevant indicators in SAGAT for reference, TSA can be measured and evaluated from three levels: team perception, team understanding, and team evaluation. An report might contain one or more TSA errors, including team perception (E1), team comprehension (E2), and team projection (E3) error. It can be seen that the three types of error are correspond to TSA level in Figure 1. The same TSA error was combined into one without double counting (Lin et al., 2010). Finally, the TSA error statistics result is shown in Figure 3. The horizontal axis represents the type of TSA error, and the vertical axis represents the number of each type of TSA error.

Among the data of 178 samples, there were one or more PSFs that trigger TSA error. Due to the limited content of reports, it is not possible to analyze related influencing factors of regulatory authorities and the government factors, so only individual factors, team factors, situational factors and organizational factors were analyzed (Lin et al., 2010) by using the established human error incident investigation method (Li et al., 2018a). The primary PSFs statistics are shown in Figure 4, combing the same PSFs into one, for example, the complexity, availability, level of detailed explanation, etc. of the more specific factor of procedure are all attributed to the factor of procedure. Similarly, the horizontal axis represents the main PSFs that trigger TSA error, and the vertical axis represents the number of each PSF. The main PSFs that affecting TSA include communication (K1), experience (K2), training (K3), severity (S1), task (S2), available time (S3), procedure (Q1), technical system (Q2), human-machine interface (Q3), external environment (A1), work supervision (A2) and safety culture (A3). Among them, communication (K1), experience (K2) and training (K3) factors mainly affect the knowledge and experience level of the operating team. Accident severity (S1), task (S2) and available time (S3) factors mainly affect the stress level of the operating team. Procedure (Q1), technical system (Q2) and human-machine interface (Q3) factors mainly affect the display quality of information. External environment (A1), work supervision (A2) and safety culture (A3) mainly affect the operators' attention and safety attitude (Li et al., 2017b; Li et al., 2021; Liu, et al., 2022). The SEM enables these PSFs to be used as observation variables to concretize latent or mediating variables such as team knowledge and experience level (Y2), team

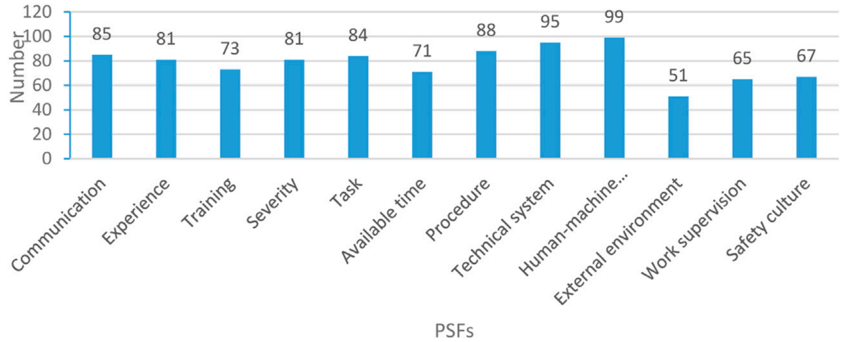

FIGURE 4
Major PSFs statistics.

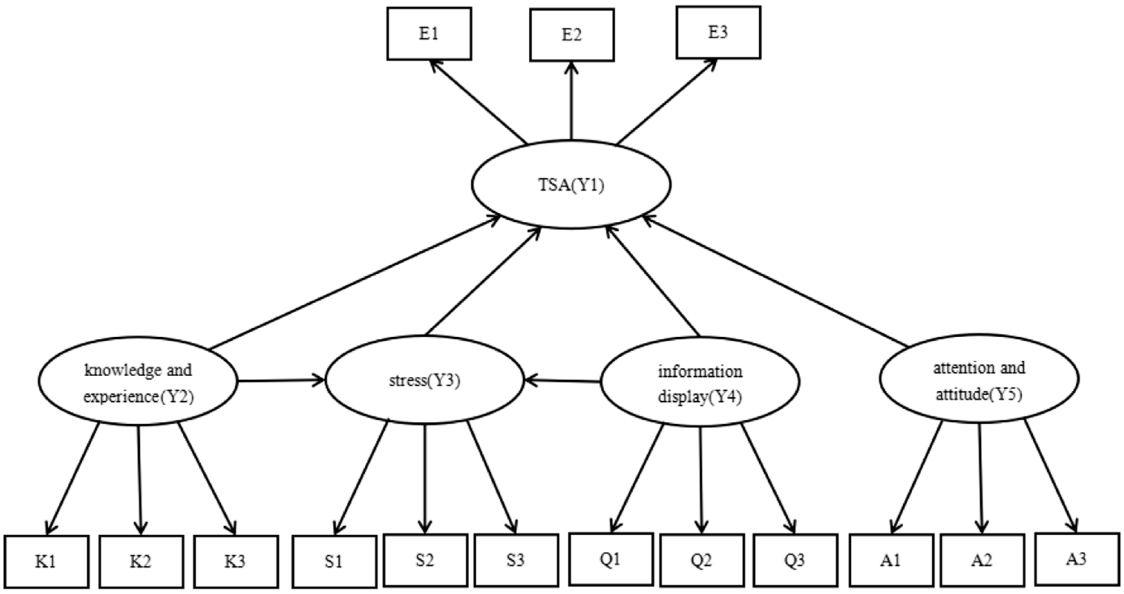

FIGURE 5
Path of structural equation model.

stress level (Y3), information display quality (Y4), attention and attitude (Y5), which are difficult to observe directly, and to establish the relationship between the latent variables, as shown in Figure 5.

Results

Model fitting results

The consistency between our hypothesis model and collected data was judged by a model-fitting index. In this paper, Mplus 8.3 software was used to analyze the structural model, and the robust weighted least squares (WLSMV) was adopted to demonstrate the relationship between the variables. The fitting degree of the model is generally verified by the following indicators (Chen et al., 2007; Wang and Chen, 2013, 2017):

(1) Chi-square (χ^2) test. The most basic fitting index is the χ^2 statistic, and most fitting indexes are evolved from it. χ^2 is used to test the difference between the covariance matrix of the measure model and the observed data. Since χ^2 is sensitive to sample size and tends to increase with the increase of sample size, the ratio of the χ^2 to degree of

TABLE 1 Model fitting indexes.

Index	χ^2	*p*	χ^2/df	RMSEA	SRMR	CFI	TLI
Recommended value	—	>0.05	<2	<0.08	<0.10	>0.95	>0.9
Model fitting index	98.685	0.088	1.218	0.035	0.088	0.973	0.965

TABLE 2 Estimation results.

ypothesis	Hypothesis path			Path coefficient	SE	T-values	*p*-values
H1a	Y4	→	Y1	0.275	0.127	2.167	0.030
H1b	Y4	→	Y3	−0.247	0.112	−2.210	0.027
H2a	Y2	→	Y1	0.398	0.125	3.197	0.001
H2b	Y2	→	Y3	−0.276	0.107	−2.572	0.010
H3	Y3	→	Y1	−0.384	0.131	−2.935	0.003
H4	Y5	→	Y1	0.249	0.110	2.263	0.024

freedom (χ^2/df) is often used to assess the model fitting in order to correct the effect of degree of freedom on χ^2. Significant χ^2 test indicates that the model fitting is not perfect, but it is generally necessary to combine other indicators to make a comprehensive judgement.

(2) Root-mean-square error of approximation (RMSEA). RMSEA is less affected by sample size and more sensitive to model missetting, so it is an ideal fitting index. McDonald and Ho (Wang, 2014) recommend RMSEA less than 0.08 as an acceptable model and less than 0.05 as an excellent model.

(3) Standardized root mean square residual (SRMR). In addition to evaluating the model from the perspective of model fitting, the fitting degree of the model can also be examined form residual. SRMR is one of the indicators to evaluate the residual directly, and its value range is between 0 and 1. When in the range of 0.08–0.10, the value indicates a mediocre fit (Hu and Bentler, 1999).

(4) Comparative fit index (CFI). Currently, CFI is one of the most robust and widely used indicators. It is insensitive to sample size and performs well in small samples. It is generally believed that the value should be greater than 0.90.

(5) Tucker-lewis index (TLI). TLI modifies the normed fit index (NFI) which is greatly affected by sample size and complexity of model. It is generally agreed that TLI greater than 0.90 indicates that the model is acceptable, and greater than 0.95 indicates that the model fits well.

The fitting results are shown in Table 1. It can be seen that all the fitting indexes reach the standards, indicating that the model fits well.

Validating model hypothesis

Model parameter results are shown in Table 2 and Figure 6, as the standardized load and path coefficients respectively. The load coefficients in the model indicate the extent to which the observed variables reflect the information of the latent variables. As shown in Figure 6, the load coefficients in this model were all greater than 0.6, indicating these observed variables could well reflect their corresponding latent variables. The path coefficients in the model indicate the degree of influence among the latent variables. The total effect was the sum of the direct and the indirect effects. According to Table 2 and Figure 6, the effects of various factors on TSA are calculated, as shown in Table 3. All influencing factors had significant effects on TSA. The hypothesis H1a (information display quality is positively related to TSA) had an acceptable strength ($\beta = 0.275$, $p < 0.05$) and a positive direction (presented in Table 2). The hypothesis H1b (information display quality is positively related to team stress level) had an acceptable strength ($\beta = -0.247$, $p < 0.05$) and a positive direction. The hypothesis H2a (team knowledge and experience level is positively related to TSA) showed an acceptable strength ($\beta = 0.398$, $p < 0.05$) and a positive direction. The hypothesis H2b (team knowledge and experience level is positively related to team stress level) had an acceptable strength ($\beta = -0.276$, $p < 0.05$) and a positive direction. The hypothesis H3 (team stress level is negatively related to TSA) showed an acceptable strength ($\beta = -0.384$, $p < 0.05$) and a negative direction. The hypothesis H4 (attention and attitude is positively related to TSA) showed an acceptable strength ($\beta = 0.249$, $p < 0.05$) and a positive direction. All of above indicated that the model hypotheses got supported.

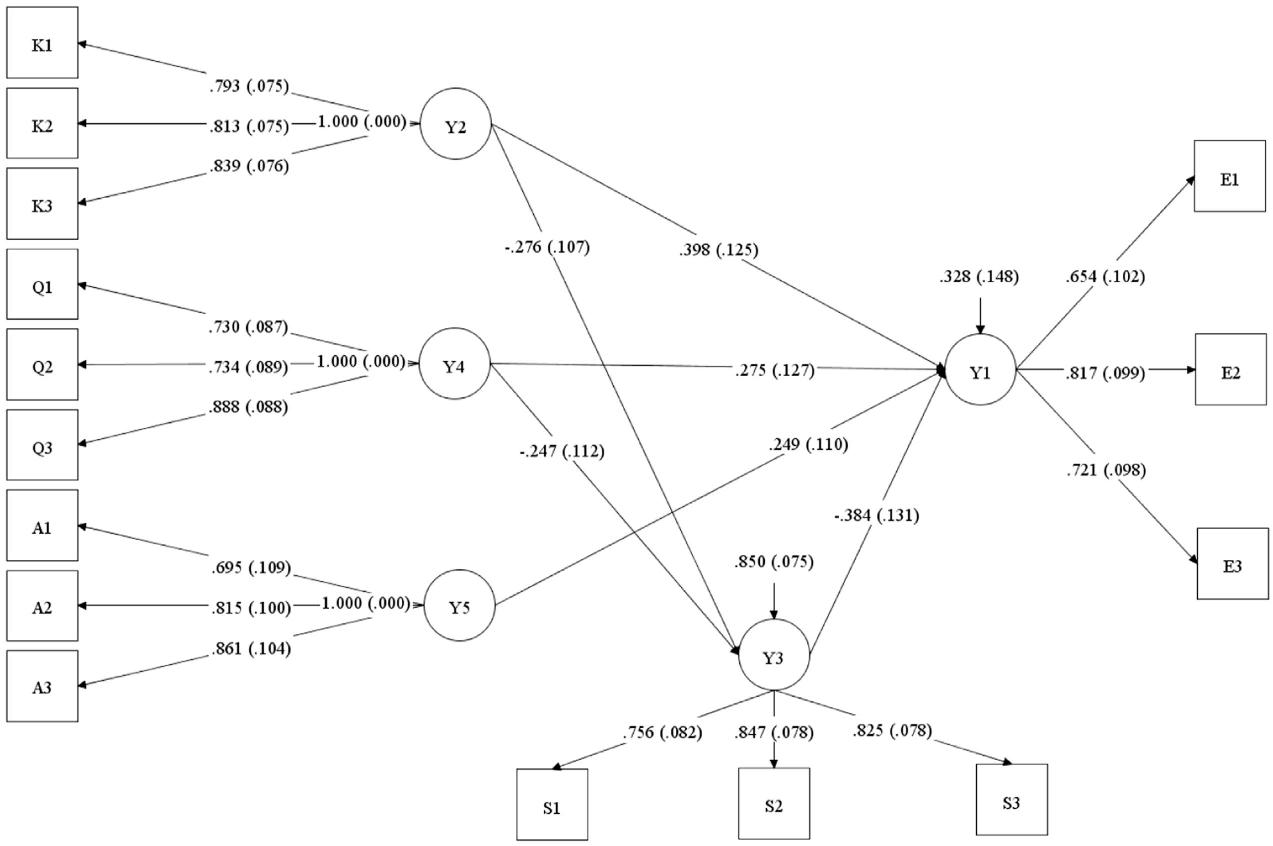

FIGURE 6
TSA influencing factors path relationship.

TABLE 3 Effects of various factors on TSA.

Effect	Team knowledge and experience level	Team stress level	Information display quality	Attention and attitude
Direct effect	0.398	−0.384	0.275	0.249
Indirect effect	0.106	—	0.095	—
Total effect	0.504	−0.384	0.370	0.249

Furthermore, communication (K1), experience (K2) and training (K3), these three factor loading coefficients of observation indicators of knowledge and experience (Y2) are 0.793, 0.813 and 0.839 respectively, indicating that the improvement of training (K3), experience (K2) and communication (K1) can effectively promote the improvement of team knowledge and experience (Y2). The factor loading coefficients of the three observation indicators of stress level (Y3) of accident severity (S1), task (S2), and available time (S3) are 0.730, 0.734, and 0.888, respectively, indicating that the available time (S3) is main influencing factors impacting stress level (Y3), the severity of the accident (S1) and the task (S2) also have an important influence, these three observation indicators can explain 85% of the influence, and the knowledge and experience level (Y2) and information display quality (Y4) also has a certain influence on stess level (Y3), which can explain 15% of the influence. Procedure (Q1), technical system (Q2), and human-machine interface (Q3), the factor loading coefficients of the observation indicators of the three information display quality (Y4) are 0.695, 0.815, and 0.861, respectively, indicating that the human-machine interface (Q3) and the technical system (Q2)) is an important factor affecting the quality of information display (Y4), and procedures (Q1) also have a certain impact; External environment (A1), work supervision (A2), safety culture (A3), these three factor loading coefficients of observation indicators of attention and attitude (Y5) are 0.756, 0.847, 0.825, respectively, indicating that work supervision (A2) and safety culture (A3) is the main influencing factor affecting attention and attitude (Y5), and the external environment (A1) also has a certain influence on attention and attitude (Y5).

Discussions

Among all factors, team knowledge and experience level had the greatest influence on TSA, which indicates that the knowledge and experience of team is the main factor in the formation and maintenance of TSA, this is consistent with the findings of the study by Li et al. (2021). Once the knowledge and experience of team is limited, TSA will be adversely affected. The knowledge and experience level of team affecting TSA is mainly influenced by communication, experience level and training. It is noted from Figure 6 that the training has greatest reflection on team knowledge and experience level. This indicates that in complex operational tasks and environments, operators need to leverage their previous training and experience, as well as ensure good communication with other members to maintain a good level of TSA.

The negative impact of team stress level on TSA indicates that excessive stress will lead to lower situation awareness. Stress may reduce the working memory capacity, limit information processing and reduce attention of operator, there by negatively affecting TSA (Liu et al., 2022). It is noted from Figure 6 that task and available time have similar reflections on stress, followed by severity. At the same time, team stress level is also affected by other factors. For instance,The level of knowledge, experience of team and the quality of information display which all affecting the level of TSA are negatively correlated with it. Experienced operators may adopt some strategies to proactively anticipate potential problems or risks, develop contingency plans, and prioritize tasks, so that they can cope with vague, dynamic conditions and time pressure. System with functions of guiding attention, integrating data, collecting and disseminating high-quality information, will reduce the complexity of tasks and relieve the stress on the operator.

Information display quality had a positive impact on TSA. A well-designed human-machine interface is conductive to the operator to grasp the dynamic information quickly and accurately and respond in time. Detailed and understandable procedures can help the operator perceive and understand task information and perform operations in accordance with the corresponding procedures (Lin et al., 2016). A good technical system avoids the negative effects caused by problems such as delay and complex system structure. These help the operator to efficiently understand the operating principle, failure mechanism, and dynamic information of system in real time, thus improving the level of TSA.

The positive impact of attention and attitude on TSA was obvious. Good attention and attitude shows that the operator is more vigilant in gathering information from a complex and dynamic work environment and valuating detected anomalies. From the load coefficient of the measurement model, safety culture better reflected attention and attitude, followed by work supervision and external environment. If the safety culture is not good, the working attitude of operator will be affected, such as the lack of risk awareness and questioning attitude, which will easily lead to TSA error, this is consistent with the findings of the study by Li et al. (2018a). Strict work supervision enable operator to paying attention to safety standards and rules and maintaining a good safety attitude at all times. Moreover, when the interference of external environment is less, the operator will pay more attention. All of this are conductive to formation of high level of TSA.

Finally, due to the limited information related to specific influencing factors of regulatory authorities and the government factors provided by incident reports and small deviation reports, which do have some effects to trace the impact of government and regulatory factors on TSA. Swain and Guttman (1983) pointed out that, actions by government regulatory have a substantial effect on plant personnel and practices. For example, if government regulatory emphasizes how the operators respond to hypothetical abnormal events, the operators will tend to think about coping with the unusual, and in this process will acquire and maintain a high level of situational awareness. Therefore, in response to this outcome, regulatory authorities and governments can positively influence TSA by issuing relevant regulations, strengthening supervision and periodic review.

Conclusion

In this study, four mediating variables (team knowledge and experience level, information display quality, attention and attitude, team stress level), and one dependent variable of TSA and 15 observed variables were selected to establish a comprehensive structural equation model for purpose of identifying which factor influences TSA most. All the preceding variables showed significant effects on TSA. Specifically, the positive effects were: team knowledge and experience level (0.504), information display quality (0.370), attention and attitude (0.249). Team knowledge and experience plays the most important role in improving TSA, which is of great significance to the education and training of operators in digital NPPs. Managers in NPPs should enhance operators training so that they have enough knowledge to perform well in abnormal conditions. Emphasis should also be placed on selecting and developing experienced operators who have the skill to identify what happened to the NPP and what state the system is in, as well as to verify and evaluate this state. Moreover, strengthening communication among team members is also a way to improve the level of knowledge and experience. The negative effect was: team stress level (−0.384). Stress depleted operators' cognitive resources. However, if human cognitive processes are fully taken into account, the system can effectively cope with severely difficult tasks and time pressure. The same is equally true and applies where the operator has knowledge and experience.

Due to the numerous influencing factors and complicated influencing relations of TSA, it is necessary to consider the influence mechanism of more specific PSFs on TSA in the future to be more conducive to the prevention of TSA error. In addition, more sample data should be collected for modeling analysis and model verification to improve the robustness of the model.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RW: Conceptualization, Investigation, Methodology, Writing-original draft. JW: Formal analysis, Investigation. PL: Writing-review and editing, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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