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Research article

An investigation into accidents in laboratories in universities in China caused by human error: A study based on improved CREAM and SPAR-H

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ABSTRACT

Although considerable research has been devoted to improving safety in university laboratories, accidents, in that environment, have still occurred frequently at the cost of serious injury or even death of laboratory personnel. Currently, few Human Reliability Analyses (HRA) have been conducted with respect to a university laboratory. The aim of the research was to conduct a reliability study relating to human behaviour in a university laboratory to explore quantitatively the causes and influencing factors relating to the frequency of laboratory accidents. Improved Cognitive Reliability and Error Analysis Method (CREAM) and improved Standardized Plant Analysis Risk HRA (SPAR-H) were employed to assess Human Error Probability (HEP) of 23 subjects. The HEP calculated through improved CREAM proved more accurate than results obtained through improved SPAR-H. Unexpectedly, the results demonstrated that under similar environmental conditions, the HEP of subjects did not decrease with an increase in educational background, including additional experimental time and experience. Moreover, environmental conditions exerted greater impact on personnel reliability than Human Inherent Factors (HIFs) in laboratories. It is anticipated that the study would provide valuable insights, in respect of research methods, and to serve as a practical basis for lowering the accident rate in university laboratories.

1. Introduction

Accidents in university laboratories have occurred frequently, which have led to serious consequences. Since 2000, as many as 99 fatalities have been documented as a consequence of 113 laboratory accidents in China. The number of accidents in university laboratories in other countries was equally depressing. Laboratories have usually been regarded as essential to university instruction and scientific research [1], however, it is a potentially hazardous working environment owing to possible risks relating to processes, with machines and chemicals [2]. It has been established that university laboratories were more hazardous than in other working environments in industrial enterprises [3]. Laboratories contain a variety of glassware, chemical reagents, gas cylinders, including reaction kettles, the presence of which poses a significant danger that may lead to safety incidents. Such events could result in the occurrence of health concerns, burns and injuries, including property damage [3–5], more importantly, serious injuries, even leading to death [6,7]. Currently, university laboratory safety measures concentrate mostly on four areas [8]: laboratory safety culture and climate [2,9–11];

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laboratory risk assessment [12–15]; laboratory safety management [16–19]; and laboratory safety education [20–22]. Few HRA, which have widely been carried out in industry, have been conducted in university laboratories [23,24]. Moreover, exhaustive and public accident investigation reports could not be consulted. Therefore, it has proved difficult to identify and quantify human errors. However, it was found that human error was the most common reason responsible for causing laboratory accidents [11,16,25]. Hence, the aim of the study was to conduct a HRA with respect to university laboratories, to study quantitatively the causes behind the frequency of such accidents, including those factors affecting personnel performance, thereby, providing guidance for future accident prevention.

HRA refers to the aspect involving Probabilistic Risk Assessment that is concerned with classifying, and analyzing the causes and results of human error [26]. The development of HRA has gone through several stages: from first generation methods that considered the effects of Performance Shape Factors (PSFs) relating to the reliability of human behaviour [27–29], to second generation methods that emphasized the effects of the environment on the reliability of human cognitive understanding [30,31], to third generation methods that focused on analyzing human errors in dynamic scenarios [32]. Recently, a hybrid model that combined second and third generation methods has been proposed [33–35]. A PSF was defined as a feature of the organization, task, or environment that specifically lowered or improved behaviour, hence, separately, improving or lessening the probability of human error.

In this paper, a method that was identified in our previous work was selected, because it had been successfully applied in industrial enterprises [36]. That method combined the CREAM and HIFs to achieve HEP. The advantage of this method was that it compensated for the lack of assessment of the impact of HIFs on performance reliability from among HRA methods. As the calculation of each HEP was derived from statistical HEPs [37–39], there existed statistical evidence behind each HRA, however, the factor relating to context that affected human performance was different for individual HRAs. In order to study the data from HRA, relating to university laboratories, more reliable and convincing, another HRA, identified as the SPAR-H method, was selected to combine with HIFs to calculate HEP. The reason why the SPAR-H was chosen was that SPAR-H was a method that had been extensively used, was easy to operate, and was applicable under extreme conditions [26,40].

The technical route, with respect to the research, was to combine research into HIFs with CREAM and SPAR-H respectively. The main objective of the study was as below: in the second part, an analysis of HIFs and the Human Factors' test was described, together with, the principal factors relating to CREAM and SPAR-H being investigated. The third section presented the research procedures for CREAM and SPAR-H, by taking high-pressure reactor operations as an example, in addition to the calculation results for HEP. In the fourth part, the calculation results concerning the two methods were compared respectively. The primary factors influencing a personnel' reliability in university laboratories were also investigated. In the final part, Conclusions were presented. The results from which could be used to examine quantitatively the phenomenon of personnel failure, including the main factors influencing the performance of personnel. It is expected to provide scientific guidance, and the basis for strengthening laboratory management and the prevention of accidents. As far as the authors understand, this research was the first time human reliability research has been used to study safety in university laboratories.

2. Materials and methods

2.1. Methods

2.1.1. Analysis of HIFs

Ethical approval was granted for this study by the Sichuan Academy of Safety Science and Technology's ethics committee (SCAKLL [2020]02), with all tests being conducted and published with the written informed consent obtained from the participants. In this study, the human factors that have led to personnel accidents in university laboratories were investigated by means of communicating with tutors and students at several local university laboratories, and, in addition, by observing students' experimental activities. Moreover, laboratory accidents, briefly reported in the media, were also researched. It was found that the main subjective factors that caused accidents to personnel were: not paying attention to the details of an operation; not observing the operating rules; not conducting a risk analysis; conducting experiments without considering the consequences; poor experimental skills; including a poor stress response when abnormal situations arose. It was further found that co-ordination of physiological factors, such as, arms and hands were the main factors relating to poor experimental skills. As a result of carelessness, students with poor hand and arm co-ordination tended to suffer from accidents, such as, injuries, breaking reagent bottles, and glassware during experiments. Lack of carefulness, patience and responsibility were psychological factors closely related to accidents. Therefore, HIFs referring to physiological and psychological factors needed to be evaluated, which included co-ordination, carefulness, patience and responsibility (see Table 1).

The impact of HIFs on performance reliability might then be evaluated. To quantify the impact of HIFs on reliability, weight factors were introduced to adjust the basic Cognitive Failure probability (CFP). The weight factors for HIFs were determined by experts' evaluation methods. By analyzing the test results for HIFs of 1035 participants from industrial firms in addition to their yearly violation

Table 1
Human intrinsic factors.

Type	HIFs		
Physiological factor	Hand and arm co-ordination capacity		
Psychological factor	Responsibility	Patience	Carefulness

records, the weight factors (see Table 2) were obtained by eight specialists in the fields of psychology, probability statistics, safety science, and behavioural science.

2.1.2. Technology roadmap

The technology roadmap for the study has been depicted in Fig. 1.

2.1.2.1. CREAM. CREAM was undertaken in conjunction with HIFs in line with four basic phases in evaluating HEP.

The initial phase consisted of constructing a sequence of events [39]. The Hierarchical Task Analysis (HTA) was used as the standard approach. It was determined that the primary task stages should be investigated with all elementary acts being identified, until the acts order of the tasks was established.

The second phase consisted of constructing an outline of the cognitive demands for the task [39]. In this phase, a task's order would be outlined in greater detail through analysing cognitive activity which constituted every elementary act. As indicated in Table 3, Cognitive functions corresponding to cognitive activity would subsequently be analyzed [39].

The third step involved an evaluation for the HIFs and Common Performance Commons (CPCs), with likely cognitive function failures being identified. Table 4 illustrated the link between CPCs and performance reliability [39]. It was necessary for the HIFs, to be appraised for a task examined in this research, and has been identified in Table 1. They comprised thirteen error categories associated with execution, planning, interpretation, and observation, with each error having a basic value concerning error probability as indicated in Table 5. Given the information of the task, an analyst was asked to determine, for each step of the task, relating to which generic failure type was most likely, based on the assessment for CPCs and HIFs.

Finally, the HEP for a certain task could be calculated. To quantify the impact of CPCs on reliability, weight factors were employed to adjust the basic CFP. Table 4 illustrated the CPCs weight factors, and total weight factor for CPCs constituted the multiplication relating to each CPC [39].

2.1.2.2. SPAR-H. SPAR-H combined with HIFs was conducted in accordance with three main steps in assessing HEP.

First ([41,42]), the Human Error Events were identified as an action or diagnosis (or combined Diagnosis and Action) to be taken. Two basic kinds of activities were employed using the same formulae and PSFs, while different values for basic Human Error Probability and PSF multipliers were employed.

Secondly, the PSFs levels were used to determine the multipliers. The context was characterised by Eight PSFs. Every PSF level was accorded an HEP multiplier value, as illustrated in Table 6 and Table 7 [41]. If "Available Time" or "Fitness for Duty" was considered a highly negative instance, following the HEP for the designated task should be set to 1 irrespective of any other multipliers involving other PSFs [43].

Thirdly, in order to obtain the HEP, based upon the number of negative PSFs, two formulae were devised. Formula (1) was employed to obtain the HEP for conditions with less than three negative PSFs, with Formula (2) being employed when three or more negative PSFs influences were present [41].

$$\text{HEP} = \text{Nominal HEP} \times \text{Composite Multipliers of PSFs} \tag{1}$$

$$\text{HEP} = \frac{\text{Nominal HEP}\blacksquare\text{Composite Multipliers of PSFs}}{\text{Nominal HEP}\blacksquare(\text{Composite Multipliers of PSFs} - 1) + 1} \tag{2}$$

Nominal HEP = 0.01 was employed for diagnosis, Nominal HEP = 0.001 for action tasks, and Composite Multipliers of PSFs constituted the multiplication of the PSF level multipliers. If a task contained aspects combining both action and diagnosis, both action and diagnosis sections should be analyzed. formulae (3) were [41]:

Table 2
The HIFs' impact on reliability and Weight factors.

HIF name	Level	Impact on reliability	CREAM				SPAR-H	
			Cognitive function				Diagnosis	Action
			OBS	INT	PLAN	EXE		
Patience	Good	Improved	0.5	1.0	1.0	0.5	0.5	0.5
	Medium	Not significant	1.0	1.0	1.0	1.0	1.0	1.0
	Insufficient	Reduced	2.0	1.0	1.0	2.0	2.0	2.0
Responsibility	Good	Improved	0.5	1.0	1.0	0.5	0.5	0.5
	Medium	Not significant	1.0	1.0	1.0	1.0	1.0	1.0
	Insufficient	Reduced	2.0	1.0	1.0	2.0	2.0	2.0
Carefulness	Good	Improved	0.5	1.0	1.0	0.5	0.5	0.5
	Medium	Not significant	1.0	1.0	1.0	1.0	1.0	1.0
	Insufficient	Reduced	2.0	1.0	1.0	2.0	2.0	2.0
Hand and arm co-ordination capacity	Good	Not significant	1.0	1.0	1.0	0.5	1.0	0.5
	Medium	Not significant	1.0	1.0	1.0	1.0	1.0	1.0
	Insufficient	Reduced	1.0	1.0	1.0	2.0	1.0	2.0

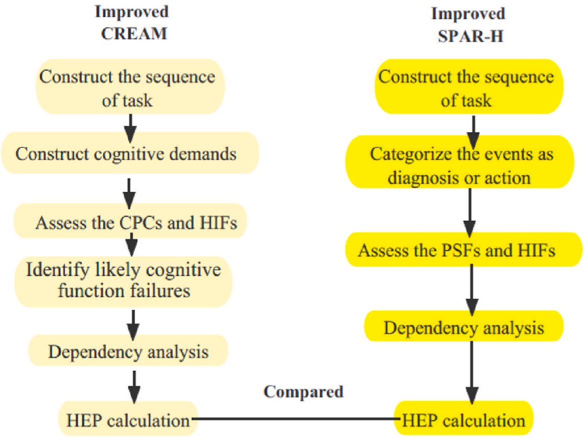

Fig. 1. Technology roadmap.

Table 3
Cognitive activity by cognitive function demand.

Cognitive Activity	Cognitive functions			
	Observation	Interpretation	Planning	Execution
Co-ordinate			◆	◆
Communicate				◆
Compare		◆		
Diagnose		◆	◆	
Evaluate		◆	◆	
Execute				◆
Identify		◆		
Maintain			◆	◆
Monitor	◆	◆		
Observe	◆			
Plan			◆	
Record		◆		
Regulate	◆			◆
Scan	◆			
Verify	◆	◆		

$$\text{HEP (diagnosis} + \text{action)} = \text{HEP (diagnosis)} + \text{HEP (action)} \tag{3}$$

2.1.3. Human factor tests

2.1.3.1. Hand and arm co-ordination assessments. In this research, hand and arm co-ordination, principally, related to finger flexibility, arm stability, arm movement, arm co-ordination, including hand co-ordination. The aforementioned indices were tested using a set of hand and arm co-ordination testing equipment (East China normal university science and education instrument Ltd, China). Finger flexibility was tested through placing a small rod through a hole in an apparatus from top to bottom, and from left to right, employing a tweezer involving the index and thumb, with a time limit required to complete the aforementioned activity, thereby indicating finger flexibility. The arm's stability was evaluated through employing a nine-hole apparatus. The participants were instructed to place a metal pen in a specified test opening for specified time without striking the bottom or sides of the aperture. The frequency with which the metal pen struck the bottom or sides of the hole indicated the arm's steadiness. By using an arm movement tester, arm movement was tested. Participants were asked to remove a cylindrical sheet with their left hand from a hole, rotate it with their right hand, and return it back from right to left in the aperture before removing the sheet with their right hand, before rotating it with their left hand, and returning it back from left to right. Once the aforementioned test had been repeated, and measuring the time spent, errors were noted. An arm coordination tester was used to assess the arm's co-ordination. Participants were required to manipulate a parallelogram apparatus with arms, and a probe was required to be shifted along a designated track. Times off the designated track, and time spent on it were automatically noted. Concerning the hand co-ordination, two knobs were turned by participants with both hands. The turn of the left knob would cause the probe to move from left to right, while the turn of the right knob would cause the probe to move up and down. The co-ordination of both hands made it possible for the probe to proceed on a circular path. Times off the circular track, and time spent on it indicated the effectiveness of hand co-ordination.

Table 4
The list of the impact on reliability and weight factors for CPCs.

CPC	Level (Score)	Impact on reliability	Cognitive function			
			OBS	INT	PLAN	EXE
Adequacy of organisation	Very efficient (9–10)	Improved	1.0	1.0	0.8	0.8
	Efficient (6–8)	Not significant	1.0	1.0	1.0	1.0
	Inefficient (3–5)	Reduced	1.0	1.0	1.2	1.2
	Deficient (0–2)	Reduced	1.0	1.0	2.0	2.0
Working Conditions	Advantageous (8–10)	Not significant	1.0	1.0	1.0	1.0
	Compatible (4–7)	Not significant	1.0	1.0	1.0	1.0
	Incompatible (0–3)	Reduced	2.0	2.0	1.0	2.0
Adequacy of MMI and operational support	Supportive (9–10)	Improved	0.5	1.0	1.0	0.5
	Adequate (6–8)	Not significant	1.0	1.0	1.0	1.0
	Tolerable (3–5)	Not significant	1.0	1.0	1.0	1.0
	Inappropriate (0–2)	Reduced	5.0	1.0	1.0	5.0
Availability of procedures/plans	Appropriate (8–10)	Improved	0.8	1.0	0.5	0.8
	Acceptable (4–7)	Not significant	1.0	1.0	1.0	1.0
	Inappropriate (0–3)	Reduced	2.0	1.0	5.0	2.0
Number of simultaneous goals	Fewer than capacity (8–10)	Not significant	1.0	1.0	1.0	1.0
	Matching current capacity (4–7)	Not significant	1.0	1.0	1.0	1.0
	More than capacity (0–3)	Reduced	2.0	2.0	5.0	2.0
Available time	Adequate (8–10)	Not significant	1.0	1.0	1.0	1.0
	Temporarily inadequate (4–7)	Not significant	1.0	1.0	1.0	1.0
	Continuously inadequate (0–3)	Reduced	5.0	5.0	5.0	5.0
Time of day	Day-time (6–10)	Not significant	1.0	1.0	1.0	1.0
	Night-time (0–5)	Reduced	1.2	1.2	1.2	1.2
Adequacy of Training	Adequate, high experience (8–10)	Improved	0.8	0.5	0.5	0.8
	Adequate, low experience (4–7)	Not significant	1.0	1.0	1.0	1.0
	Inadequate (0–3)	Reduced	2.0	5.0	5.0	2.0
Crew collaboration quality	Very efficient (9–10)	Improved	0.5	0.5	0.5	0.5
	Efficient (6–8)	Not significant	1.0	1.0	1.0	1.0
	Inefficient (3–5)	Not significant	1.0	1.0	1.0	1.0
	Deficient (0–2)	Reduced	2.0	2.0	2.0	5.0

Table 5
Generic cognitive function failures.

Cognitive Function	Generic failure type		Basic values
Observation	O1	Wrong object observed	0.001
	O2	Wrong identification	0.007
	O3	Observation not made	0.007
Interpretation	I1	Faulty diagnosis	0.02
	I2	Decision error	0.01
	I3	Delayed interpretation	0.01
Planning	P1	Priority error	0.01
	P2	Inadequate plan	0.01
Execution	E1	Action of wrong type	0.003
	E2	Action at wrong time	0.003
	E3	Action on wrong object	0.0005
	E4	Action out of sequence	0.003
	E5	Missed action	0.003

2.1.3.2. Psychological test. With respect to personality evaluation, a generally stable psychological trait needing consistency, stability, and individuality was required. Therefore, behaviour in several domains of life and work might be applied to predict personality evaluation [44]. In this study, Cattell's 'Sixteen Personality Factors' (16 PF) questionnaire was utilized to perform the personality evaluation experiment. The 16 PF questionnaire is regarded as one of the most significant psychological scales in the world, containing both adequate reliability and validity [45]. There were 185 items on the scale that assessed 16 dimensions. In accordance with the criteria [46], a subject who attained high perfectionism tended to pay more attention to details than one who scored low on perfectionism. People attaining high rule-consciousness tended to be thorough, while a subject who scored low on rule-consciousness would often make mistakes in operations, which could lead to accidents. And people with low tenseness tended to be patient. Therefore, perfectionism, rule-consciousness and Tenseness could be treated as indicators to measure carefulness, compliance and patience. By employing psychological test software (HUA XIN KE JIA Ltd, China), this article measured the scores and evaluation findings of 16 PF. The maximum time to finish the 16 PFs was half an hour.

2.1.3.3. Rating of the test results. Similar to the CPCs and the PSFs, both needed to be rated to determine the multipliers. The test results of HIFs also needed to be rated to determine the factor that corrected error probability. In this research, the rating of the test

Table 6
PSFs for the diagnosis tasks.

PSFs	PSFs Levels	Multiplier for Diagnosis
Available Time	Inadequate time	HEP = 1.0
	Barely adequate time	10
	Nominal time	1
	Extra time	0.1
	Expansive time	0.01
Stress/Stressors	Extreme	5
	High	2
	Nominal	1
Complexity	Highly complex	5
	Moderately complex	2
	Nominal	1
	Obvious diagnosis	0.1
Experience/Training	Low	10
	Nominal	1
	High	0.5
Procedures	Not available	50
	Incomplete	20
	Available, but poor	5
	Nominal	1
	Diagnostic/symptom oriented	0.5
Ergonomics/HMI	Missing/Misleading	50
	Poor	10
	Nominal	1
	Good	0.5
Fitness for Duty	Unfit	HEP = 1.0
	Degraded Fitness	5
	Nominal	1
Work Processes	Poor	2
	Nominal	1
	Good	0.8

Table 7
PSFs for the action tasks.

PSFs	PSFs Levels	Multiplier for Action
Available Time	Inadequate time	HEP = 1.0
	Barely adequate time	10
	Nominal time	1
	Extra time	0.1
	Expansive time	0.01
Stress/Stressors	Extreme	5
	High	2
	Nominal	1
Complexity	Highly complex	5
	Moderately complex	2
	Nominal	1
Experience/Training	Low	3
	Nominal	1
	High	0.5
Procedures	Not available	50
	Incomplete	20
	Available, but poor	5
	Nominal	1
Ergonomics/HMI	Missing/Misleading	50
	Poor	10
	Nominal	1
	Good	0.5
Fitness for Duty	Unfit	HEP = 1.0
	Degraded Fitness	5
	Nominal	1
Work Processes	Poor	5
	Nominal	1
	Good	0.5

results was based on sample data. Nearly 1400 subjects were collected for the sample data, including 1035 front-line workers from industrial enterprises, along with 350 doctors, masters' students and undergraduates from local universities. The Statistical Package for the Social Sciences (SPSS v22.0) was used to analyse the test data. Subjects' test results were evaluated by using a systematic cluster analysis approach. The data recording the shortest measurement were classified into one class through computing the Euclidean metric of the data that were separated into 3 groups. Test results were finally assessed as: poor, medium, or. good.

3. Results

The functioning of high-pressure reactors in university laboratories would involve the management of pressure vessels, which could be highly dangerous. Accidents caused through the control of high-pressure reactors are frequent. Therefore, in this paper, high pressure reactor operations in a university laboratory were taken as an example to conduct human reliability research. The laboratory operators involved PHDs, postgraduates and undergraduates.

3.1. *Construct event sequence*

The sub-tasks, elementary actions and event sequences involving high-pressure reactor operations were analyzed by employing the HTA method, as shown in Table 8.

3.2. *The evaluation results of CPCs , PSFs and HIFs*

CPCs and PSFs were evaluated through an on-site assessment of experimental sites, with reference to laboratory management systems, observation of students' experiments, and communication with students. It was found that the laboratories under investigation were not equipped with safety management personnel, safety management systems were not comprehensive enough, no operating procedures were formulated for relevant operations, including no systematic safety training being conducted for students, under high academic pressure. The evaluation results of CPCs and PSFs and their corresponding weight factors were illustrated in Table 9 and Table 10, as follows.

The test of HIFs were conducted with 23 students, who were required to operate a high-pressure reactor daily, with patience, carefulness, hand and arm co-ordination, and responsibility of the subjects being evaluated. The assessment results have been presented in Table 11.

3.3. *Identify likely cognitive function failures to calculate HEP by utilizing CREAM and SPAR-H*

With respect to the evaluation results of CPCs and HIFs, the likely cognitive function failures in high-pressure reactor operations were identified, as indicated in Table 12. Further, in accordance with analysis steps of SPAR-H, elementary actions regarding high-pressure reactor operations as diagnostic and/or action were categorized.

Taking the HEP calculation of Subject 1 as an example, weight factors of HIFs for CREAM and SPAR-H have been provided in Table 13 and Table 14. Table 15 illustrated modifications relating to Cognitive failure probability under the influence of CPCs, PSFs and HIFs. Formula (4) and formula (5) concerning the adjusted CFP for CREAM and adjusted HEP for SPAR-H were as follows:

$$\text{CFP}_{\text{adjusted}} = \text{CFP}_{\text{basic}} \times \text{CPCs}_{\text{total weight factor}} \times \text{HIFs}_{\text{total weight factor}} \tag{4}$$

$$\text{HEP}_{\text{adjusted}} = \text{HEP}_{\text{basic}} \times \text{PSFs}_{\text{total weight factor}} \times \text{HIFs}_{\text{total weight factor}} \tag{5}$$

Once the HEP for each elementary action was obtained, the final step was to incorporate the HEP relating to each elementary action into a hierarchical task analysis shown in Table 8 to attain the HEP for sub-tasks by considering the dependency of elementary actions,

Table 8
High-pressure reactor operation steps.

Event sequence	Sub-tasks	Elementary Action
1.1	Preparation	Prepare the experimental tools
1.2		Examine the Electrical circuit
1.3		Inspect the Kettle mouth gasket
2.1	Gas-tight test	Tighten the reactor cover
2.2		Add the nitrogen
2.3		Decompress
3.1	Experimental process	Charge
3.2		Inspect the reaction equipment and facility
3.3		Turn on magnetic agitating and cooling system
3.4		Heat up the reactor
3.5		Observe the response
3.6		Turn off the power
3.7		Reclaimer
4.1	Cleaning	Clean the Reactor

Table 9

The impact on reliability and weight factors for CPCs.

CPC	Level	Impact on reliability	Cognitive function			
			OBS	INT	PLAN	EXE
Adequacy of organisation	Deficient	Reduced	1.0	1.0	2.0	2.0
Working Conditions	Compatible	Not significant	1.0	1.0	1.0	1.0
Adequacy of MMI and operational support	Adequate	Not significant	1.0	1.0	1.0	1.0
Availability of procedures/plans	Inappropriate	Reduced	2.0	1.0	5.0	2.0
Number of simultaneous goals	Matching current capacity	Not significant	1.0	1.0	1.0	1.0
Available time	Adequate	Not significant	1.0	1.0	1.0	1.0
Time of day	Day-time	Not significant	1.0	1.0	1.0	1.0
Adequacy of Training	Inadequate (0–3)	Reduced	2.0	5.0	5.0	2.0
Crew collaboration quality	Efficient (6–8)	Not significant	1.0	1.0	1.0	1.0
Total weight factor for the CPCs			4.0	5.0	50.0	8.0

Table 10

PSFs for the diagnostic and action tasks.

PSFs	PSFs Levels	Multiplier for Diagnosis	Multiplier for Action
Available Time	Nominal time	1	1
Stress/Stressors	High	2	2
Complexity	Moderately complex	2	2
Experience/Training	Low	10	3
Procedures	Incomplete	20	20
Ergonomics/HMI	Nominal	1	1
Fitness for Duty	Nominal	1	1
Work Processes	Nominal	1	1
Total weight factor for the PSFs		800	240

Table 11

HIFs' evaluation of participants.

HIFs	Patience	Responsibility	Carefulness	Hand and arm co-ordination	Total weight factor for HIFs
No.	Level	Level	Level	Level	
Subject 1	Good	Good	Medium	Medium	0.25
Subject 2	Medium	Medium	Good	Medium	0.5
Subject 3	Medium	Poor	Poor	Good	2
Subject 4	Poor	Medium	Poor	Medium	4
Subject 5	Medium	Poor	Poor	Medium	4
Subject 6	Medium	Poor	Medium	Good	1
Subject 7	Medium	Good	Medium	Good	0.25
Subject 8	Good	Poor	Poor	Good	1
Subject 9	Good	Medium	Good	Medium	0.25
Subject 10	Medium	Medium	Good	Medium	0.5
Subject 11	Medium	Medium	Medium	Medium	1
Subject 12	Medium	Poor	Poor	Medium	4
Subject 13	Good	Good	Good	Poor	0.25
Subject 14	Good	Good	Good	Good	0.0625
Subject 15	Medium	Medium	Poor	Medium	2
Subject 16	Good	Good	Good	Good	0.0625
Subject 17	Poor	Medium	Medium	Good	1
Subject 18	Good	Medium	Medium	Poor	1
Subject 19	Medium	Good	Poor	Good	0.5
Subject 20	Good	Medium	Good	Good	0.125
Subject 21	Good	Medium	Poor	Good	0.5
Subject 22	Good	Good	Medium	Medium	0.25
Subject 23	Poor	Medium	Poor	Medium	4

in order for the total HEP to be calculated for the complete task. It was necessary to formulate rules. The study used formulae (6), formulae (7), formulae (8), formulae (9), formulae (10), formulae (11) and formulae (12) presented in Table 16 [43,47]. With reference to Table 16, a high-pressure reactor operation comprised four sub-tasks, with each sub-task containing elementary actions. A reliability block diagram for each sub-task was constructed, as shown in Fig. 2. A sub-task preparation consisted of three elementary actions, that comprised separate processes in order that each elementary action was not influenced by whether other actions were successful or not, which revealed that there was low dependency among elementary actions for sub-task preparations. The condition for the sub-task gas-tight test was similar to sub-task preparation. For the sub-task experimental process, elementary actions 3.1, 3.2,

Table 12
The likely cognitive function failures during High-pressure reactor operation steps.

Event sequence	Elementary Actions	Cognitive activity	CREAM								SPAR-H	
			Observation errors			Execution errors					Diagnostic	Action
			O1	O2	O3	E1	E2	E3	E4	E5		
1.1	Prepare the experimental tools	Execute						◆				◆
1.2	Examine the Electrical circuit	Execute								◆	◆	
1.3	Inspect the Kettle mouth gasket	Execute								◆	◆	
2.1	Tighten the reactor cover	Execute				◆						◆
2.2	Adding the nitrogen	Execute						◆				◆
2.3	Decompress	Execute				◆						◆
3.1	Charge	Execute						◆				◆
3.2	Inspect the reaction equipment and facility	Execute								◆	◆	
3.3	Turn on magnetic stirring system and cooling system	Execute					◆					◆
3.4	Heat up the reactor	Execute						◆			◆	
3.5	Observe the response	Observe	◆								◆	
3.6	Turn off the power	Execute								◆		◆
3.7	Reclaimer	Execute					◆					◆
4.1	Clean the Reactor	Execute				◆						◆

3.3, 3.4, 3.5 possessed high dependency in the serial system, configured as R3-1. The success or failure of R3-1 did not affect the Elementary actions 3.6 and 3.7, consequently, 3.6 and 3.7 were configured as R3-2 separately. Finally, total reliability with respect to high-pressure reactor operations could be obtained from the block diagram depicted in Fig. 3. A high-pressure reactor operation would be deemed unsuccessful as any of the sub-tasks failed, consequently, the highest error probability relating to the subtasks was allocated as the error probability for the complete task.

After CFP_i or HEP was calculated, the final operational error probability for the high-pressure reactor operation was attained by employing formulae (13):

$$HEP = 1 - \prod_{i=1}^{n} (1 - CFP_i) \tag{13}$$

where CFP_i signified a CFP adjustment, with n representing step number for the target operation, the final HEP corresponding to CREAM and SPAR-H for all subjects has been illustrated in Table 17.

3.4. Retrospective analysis

A retrospective method relating to CREAM was employed to analyse the principal causes that might have resulted in accidents. Based on the failure of human cognitive activities, the root causes of human errors were explored by analyzing internal mechanisms together with correlation processes relating to errors. The retrospective analysis constituted the following steps [39].

1. **Describe the possible error modes.** Analyzing human error accidents that occurred in laboratories, the error modes could be categorized as: negligence, forgetting, error, and violation, as presented in Table 18.
2. Establishment of an antecedent classification Table. With reference to a cause analysis associated with human error accidents that have taken place in laboratories, the factors that might have led to those accidents were divided into four aspects: human, technological, organizational, and environmental. Therefore, the relevant antecedents could be categorized into four types: human related antecedents, technological related antecedents, organizational related antecedents, and environmental related antecedents. Each type of antecedent could be further subdivided into several antecedents. Therefore, the human error antecedent classification Table that applied to laboratories was introduced, as shown in Table 19:
3. Establishment of error modes–antecedent, consequence–antecedent traceability table. Based on the human error modes and antecedent classification, combined with the work and request of laboratories, in addition to the investigation relating to accidents, the antecedents of four error modes were determined, as shown in Table 20:

With respect to a specific human error mode, it was considered necessary to trace it to its antecedents. If the antecedents could not be further determined, then it was judged that the specific antecedents were the original source of the problem. Alternatively, tracing would continue assuming the antecedent as a consequence until the root cause had been found. Based on this principle, a consequence-antecedent traceability table suitable for university laboratories was constructed, as shown in Table 21. The antecedents of H7, O4, E1, E2, and E3 could not be determined, therefore, they were the root causes.

Table 13
Weight factors of Subject 1’ HIFs for CREAM.

HIF name	No.	Level	Cognitive function failure for each step													
			1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	4.1
			E3	E5	E5	E1	E3	E1	E3	E5	E2	E3	O1	E5	E2	E1
Patience	Subject 1	Good	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Responsibility		Good	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Concentration capacity		Medium	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Arms and hands co-ordination capacity		Medium	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total impact of HIFs			0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Table 14
Weight factors of Subject 1’ HIFs for SPAR-H.

HIF name	No.	Level	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	4.1
			Action	Diagnosis	Diagnosis	Action	Action	Action	Action	Diagnosis	Action	Diagnosis	Diagnosis	Action	Action	Action
Patience	Subject 1	Good	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Responsibility		Good	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Concentration capacity		Medium	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Arms and hands co-ordination capacity		Medium	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total impact of HIFs			0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Table 15
The appraisal of Cognitive failure probability of Subject 1.

Event sequence	Elementary Actions	Likely cognitive function failures	CREAM				SPAR-H			
			Basic value	Total weight factor of CPCs	Total weight factor of HIFs	Adjusted CFP	Basic value	Total weight factor of PSFs	Total weight factor of HIFs	Adjusted HEP
1.1	Prepare the experimental tools	Action on wrong object	0.0005	8.0	0.25	0.001	0.001	240	0.25	0.03
1.2	Examine the Electrical circuit	Missed action	0.003	8.0	0.25	0.006	0.01	800	0.25	0.7
1.3	Inspect the Kettle mouth gasket	Missed action	0.003	8.0	0.25	0.006	0.01	800	0.25	0.7
2.1	Tighten the reactor cover	Action of wrong type	0.003	8.0	0.25	0.006	0.001	240	0.25	0.2
2.2	Adding the nitrogen	Action on wrong object	0.0005	8.0	0.25	0.001	0.001	240	0.25	0.2
2.3	Decompress	Action of wrong type	0.003	8.0	0.25	0.006	0.001	240	0.25	0.2
3.1	Charge	Action on wrong object	0.0005	8.0	0.25	0.001	0.001	240	0.25	0.2
3.2	Inspect the reaction equipment and facility	Missed action	0.003	8.0	0.25	0.006	0.01	800	0.25	0.7
3.3	Turn on magnetic stirring system and cooling system	Action at wrong time	0.003	8.0	0.25	0.006	0.001	240	0.25	0.2
3.4	Heat up the reactor	Action on wrong object	0.0005	8.0	0.25	0.001	0.01	800	0.25	0.7
3.5	Observe the response	Wrong object observed	0.001	4.0	0.25	0.002	0.01	800	0.25	0.7
3.6	Turn off the power	Missed action	0.003	8.0	0.25	0.006	0.001	240	0.25	0.2
3.7	Reclaimer	Action at wrong time	0.003	8.0	0.25	0.006	0.001	240	0.25	0.2
4.1	Clean the Reactor	Action of wrong type	0.003	8.0	0.25	0.006	0.001	240	0.25	0.2

Table 16
Calculations for the HEP of a task involving fundamental actions.

Logical relation between elementary actions	Dependency between elementary actions	HEP of the sub-task
Parallel elementary actions	High dependency	$HEP_{\text{sub-Task}} = \text{Min}\ (HEP_{\text{elementary actioni}})$ (6) Or $R_{\text{Task}} = \text{Max}\{R_{\text{sub-Task i}}\}$ (7)
	Independent/low dependency	$HEP_{\text{sub-Task}} = \prod HEP_{\text{elementary-action I}}$ (8) Or $R_{\text{Task}} = 1\text{-}\prod(1\text{-}R_{\text{sub-task i}})$ (9)
Sequential elementary actions	High dependency	$HEP_{\text{sub-Task}} = \text{Max}\ (HEP_{\text{elementary-action i}})$ (10)
	Independent/low dependency	$HEP_{\text{sub-Task}} = 1\text{-}\prod(1\text{-}HEP_{\text{elementary-action i}}) \approx \sum HEP_{\text{elementary-action I}}$ (11) Or $R_{\text{Task}} = \prod(R_{\text{sub-task i}})$ (12)

4. Discussion

It was found that the HEP calculated by SPAR-H was significantly higher than that calculated by CREAM, as shown in Table 17. Tutors and subject students believed that the HEP calculated by CREAM was more appropriate. Moreover, the fact that there were 21 minor injuries as a result of operating the reactor in this laboratory in 2021 has been recorded in the laboratory's safety management file. With reference to Heinrich's Law, the proportion of major, minor, and no-injury accidents were 1:29:300 based upon a survey of over than 75,000 industrial accident reports [48]. Therefore, it could be calculated that there would be, approximately, 217 unsafe behaviors relating to reactor operations. According to Table 8, the high-pressure reactor operation involved a total of 14 operational behaviors. Approximately, 11,592 operation behaviors in this year's calculation were based on the frequency of each student operating the reactor once a week on average (based on 4 weeks per month and 9 months per year except for winter and summer vacations), thus, the average incidence of unsafe behaviors was approximately 0.02. According to Table 17, the average HEP values of the 23 subjects calculated by SPAR-H and CREAM were 0.384 and 0.062, respectively. Therefore, it could be seen that the HEP calculated by CREAM was closer to the actual situation. Consequently, we had reason to believe that compared with SPAR-H, the HEP calculated by CREAM was more accurate and effective. The reason why the HEP calculated by SPAR-H was significantly higher than that calculated by CREAM could be attributed to the total weight factor for the PSFs because SPAR-H was as high as 800 and 240, while the total weight factor for the CPCs associated with CREAM was 50.

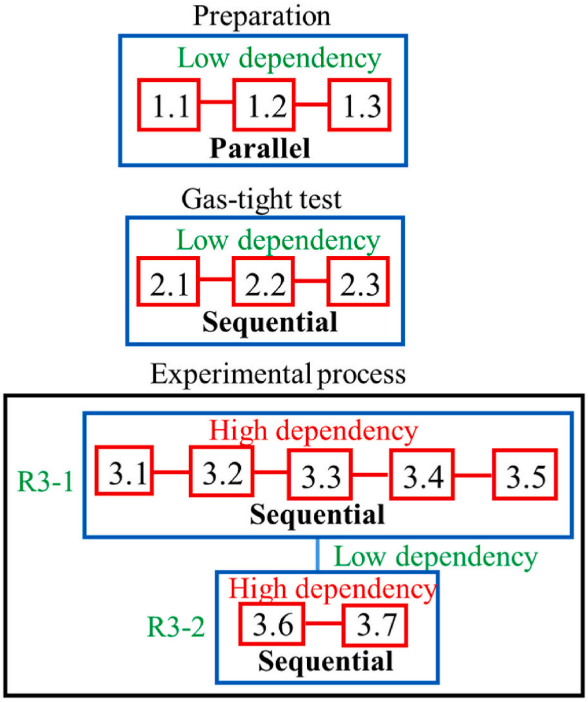

Fig. 2. Fundamental action reliability block diagram of the whole operation.

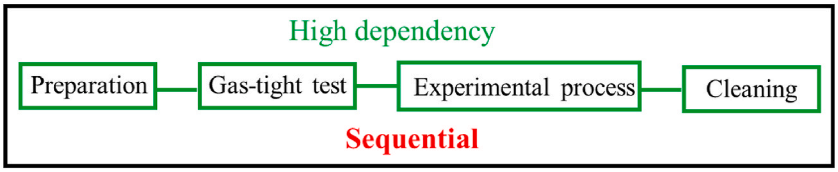

Fig. 3. Sub-task reliability block diagram of the complete operation.

It was seen that there was no significant regularity occurring in the HEP of undergraduates, postgraduates and doctoral students, as shown in Fig. 4. The HEP for undergraduates and postgraduates was as high as 0.196, and that of doctoral students was as high as 0.1. Significantly, the HEP of PHD and postgraduates could be regarded as similar to that of undergraduates, or even higher than that of undergraduates. The HEP for PHD students could also be similar to that of postgraduates, or even higher than that of postgraduates. It could be seen that HEP did not decrease with an increase in educational background, experimental time and experience. It was concluded that under similar conditions of CPCs, the main factors that affected HEP were: patience, responsibility, and carefulness, including other innate HIFs that were difficult to change through acquired factors. These HIF factors possessed no correlation with educational background. The average HEP for PHDs, postgraduates and undergraduates were 0.0366, 0.0466, and 0.113, respectively. The reason behind this trend was that students with higher intrinsic qualities, such as: patience, responsibility, and carefulness, were more inclined to continue to study for a master's degree or a doctoral degree.

In order to investigate which of the CPCs and HIFs exerted a greater impact on the performance of laboratory personnel, the HEP, under the assumption that the combined weight factor for the CPCs was 1 or the combined weight factor for the HIFs was 1, was calculated. The comparison between the two calculation results, and the HEP calculated by CREAM was shown in Table 22. It was found that if the combined weight factor for the CPCs was 1, the average HEP was 0.008, while, if the combined weight factor for an HIF was 1, the HEP was 0.051. Obviously, under the assumption that the combined weight factor for an HIF was 1, HEP was closer to 0.062. It could be seen that the main factors affecting personnels' performance in university laboratories were environmental conditions referred to as CPCs or PSFs. The research results were consistent with the conclusions in the literature [49] where hybrid methods, including the Bayesian network, Human Factors Analysis and Classification System, and Fuzzy set theory, were used to analyse the most factors contributing to Human errors in fires and explosions occurred in laboratories. This differed from those in industrial enterprises. Compared with laboratories, industrial enterprises paid more attention to safety, therefore, more strict safety management systems had been specified, and more resources were made available [50,51]. As a result, industries must be equipped with a safety management department, including full-time safety management personnel. Contextual conditions, commonly, did not exert a negative impact on personnels' reliability. Therefore, HIFs were the main factors that affected personnels' reliability in

Table 17
HEP $_{CREAM}$ and HEP $_{SPAR\text{-}H}$ of the subjects.

Number.	Education background	CREAM	SPAR-H
		HEP_{CREAM}	$HEP_{SPAR\text{-}H}$
Subjects 1	Postgraduate	0.013	0.161
Subjects 2	Postgraduate	0.026	0.288
Subjects 3	Postgraduate	0.1	0.308
Subjects 4	Undergraduate	0.196	0.867
Subjects 5	Postgraduate	0.196	0.867
Subjects 6	Postgraduate	0.051	0.524
Subjects 7	Postgraduate	0.013	0.161
Subjects 8	PHD	0.051	0.524
Subjects 9	Postgraduate	0.013	0.161
Subjects 10	Undergraduate	0.026	0.288
Subjects 11	Postgraduate	0.051	0.524
Subjects 12	Undergraduate	0.196	0.867
Subjects 13	Undergraduate	0.013	0.161
Subjects 14	PHD	0.003	0.044
Subjects 15	PHD	0.1	0.308
Subjects 16	PHD	0.003	0.044
Subjects 17	Postgraduate	0.051	0.524
Subjects 18	Undergraduate	0.051	0.524
Subjects 19	PHD	0.026	0.288
Subjects 20	Postgraduate	0.006	0.085
Subjects 21	Postgraduate	0.026	0.288
Subjects 22	Postgraduate	0.013	0.161
Subjects 23	Undergraduate	0.196	0.867

Table 18
Error modes in laboratories.

Error modes	Form
Negligence	Warnings ignored, distractions, temporary disturbance, principally
Forgetfulness	Forgetting to operate tasks, missing operations, in particular
Error	Error in understanding, error relating to inference, error in identification, and error in operation, in particular
Violation	Operations that violated regulations, violation in safety regulations

industrial enterprises.

5. Conclusion

The purpose of the study was to conduct human reliability research into safety in university laboratories, and to explore phenomenon and influencing factors concerning the frequency of accidents from a new perspective. The study is expected to offer guidance for the prevention involving accidents. This study found that the HEP calculated by improved CREAM was more reliable than that calculated by improved SPAR-H. Unexpectedly, the calculation results revealed that under similar environmental conditions, the HEP for students did not decrease with an increase in educational background, including an increase in experimental time and experience. Moreover, environmental conditions exerted greater impact on personnels' reliability than HIFs in laboratories.

With reference to the retrospective analysis of the principal causes concerning laboratory accidents, suggestions for reducing human errors were proposed as follows: Fundamentally, importance should be attached to safety training, to ensure sufficient training intensity and time, with regular practical training provided, and updated training content appropriately. Relaxing safety training and education for PHD or post-doctoral candidates should be avoided. Furthermore, a good safety cultural environment should be encouraged, critical safety management work from aspects, such as, organization, safety management personnel allocation, and system establishment should be put in place, to avoid the relevant root causes described in Table 21. Finally, students with unsatisfactory HIFs' evaluation should be educated thoroughly. For instance, tutors should strengthen the responsibility education for students with a poor sense of responsibility. The measures that could be taken are as follows: to clarify the safety responsibility of students, to improve their awareness of responsibility by using reasoned arguments, and to cultivate their sense of responsibility under pastoral care. The subjects with poor hand and arm co-ordination capacity should be given one-to-one guidance, and face-to-face teaching. It is believed that the power of education could encourage students to attach increasing importance to safety.

The limitations of this study were: an absence in the research concerning how far human error had been improved. The next step would be to examine about how far human errors had been improved in the laboratory. Moreover, two aspects would be mainly researched. On the one hand, how far environmental factors, such as, organizational factors, and systems had been improved. On the other hand, whether psychological factors could be improved, including and how far psychological factors had been improved would need to be focused on.

Table 19
Human error antecedent classification.

Type	No.	Name	Meanings
Human	H1	Error identification	Incorrect recognition of pressure gauge reading.
	H2	Delayed interpretation	Judgment and handling timing for faults, sudden problems, and temporary dangerous delays.
	H3	Decision errors	Incorrect, irrational, and unilateral decisions.
	H4	Diagnosis errors	Incorrect and incomplete judgment concerning experimental status and facility equipment failures.
	H5	Inappropriate or incorrect planning	Inappropriate planning might lead to difficulties in implementation and failure to achieve expected goals.
	H6	Poor attitude to work	Laziness, lack of care, taking shortcuts, poor sense of responsibility, poor safety awareness, and poor awareness of rules.
	H7	Cognition preference	Blind self-confidence, subjective speculation, along with further incorrect decisions and cognition.
	H8	Performance Variability	Inadequate training would lead to unstable performance.
	H9	Distraction/inattention	Distractions and lack of concentration would lead to information and signals missing owing to physiological and psychological factors.
	H10	Psychological/ physiological factors	Psychological factors：Patience, Conscientiousness, Responsibility, leadership, Communication and co-operation, principally; physiological factors: anti-fatigue pressure, poor hand and arm co-ordination, concentration, including poor memory, principally.
	H11	Poor skill	Inadequate training in skills and safety procedures might result in inadequate experimental proficiency, unfamiliarity with rules and regulations, inability to identify hidden dangers, and inability to avoid visible hazards.
Technology	T1	Equipment failure	Failure of experimental facilities and equipment, operations' equipment with defects or inability to operate normally; inadequate maintenance and management of equipment, damage to equipment, primarily.
	T2	Infeasible or restricted Operation	Inability to achieve a goal; unable to achieve expected results owing to the influence of the operation; unable to operate smoothly because of inappropriate design.
	T3	Incomplete regulations	Obsolete regulations, unclear and incomplete regulations, and defects in management regulations.
Organization	O1	Ineffective skill training	Inadequate skill training might result in personnel's experimental skills not meeting ideal requirements.
	O2	Ineffective knowledge training	Inadequate theoretical knowledge training might lead to knowledge deficiencies among experimental personnel, leaving them vulnerable in the face of unexpected events.
	O3	Ineffective safety education	Insufficient safety education might lead to a poor safety culture atmosphere and personnel safety awareness.
	O4	Management	Flaws in the rules and regulations; inappropriate organizational establishment; lack of strict safety supervision, incomplete execution, principally.
	O5	Unreasonable demands	Excessive task allocation would lead to insufficient resources/time or excessive task demands; tutors have overly strict requirements for students.
	O6	Irregular working	Inadequate work time management; nighttime experiments.
Environment	E1	Poor environment	Adverse environments, such as, thunderstorms, coldness, high temperatures, or earthquakes, principally.
	E2	Poor working environment	The workspace is confined; poor air circulation; awful smell.
	E3	Environmental change	Temporary dangerous situations, emergencies, unexpected problems.

Table 20
Error mode–antecedents.

Error modes	Antecedents
Negligence	P6,P7,P8,P9,P10,T1,T2,O3,O5,O6,E1
Forgetfulness	P2,P5,P6,P9,P10,T3,O1,O2,O4,O6,E1
Error	P1,P3,P5,P6,P7,P8,P10,P11,T1,T2,T3,O1,O3,E3
Violation	P2,P6,P7,P11,T2,T3,O1,O2,O3,O4,05

Data availability statement

Because the research data contained confidential information, it was decided not to deposit the data into a publicly available repository.

Statement

The authors declare that ethical approval was granted for this study by the SiChuan Academy of Safety Science and Technology's ethics committee (SCAKLL [2020]02), and all tests were conducted and published with the written informed consent obtained from the participants.

CRediT authorship contribution statement

Ye He: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Nian-Sheng Kuai:** Data curation, Formal analysis, Investigation. **Li-Min Deng:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Zi-Li Wang:**

Table 21
Consequent-antecedents.

Consequence	Antecedent	Root cause
H1 Error identification	P4, P9, P10,T2, O1, E3	Visual error
H2 Delayed interpretation	P1, P10, T1, T3, O2	Facility equipment failure, lack of knowledge.
H3 Decision errors	P1, P6, P7, P9, P10, O2	Lack of corresponding knowledge and skills, incomplete consideration, and poor psychological factors.
H4 Diagnosis errors	P1, P6, P7, P10, T3, O1, O2, E3	Empiricism, multiple interferences.
H5 Inappropriate or incorrect planning	P3, P4, P9, O2, O5	Identifying incorrect goals, inadequate training, incomplete planning, principally.
H6 Poor attitude to work	P10, T3, O3, O4	Lack of responsibility, inadequate supervision, high task pressure, and low awareness of safety responsibility.
H8 Performance Variability	T1, O1, O5, O6	Lack of training, physiological factors, and task changes.
H9 Distraction/inattention	P10, T1, T2, T3, E1, E2, E3	Fatigue, personnel interference, short-term experiments, inability to perform experimental work, in particular.
H10 Psychological/ physiological factors	O2, O5, O6, E1, E2	Poor patience, conscientiousness, responsibility, communication and co-operation, in particular poor response to tiredness, including poor hand and arm co-ordination, inattention, inadequate reaction ability and memory, principally.
H11 Poor skill	P8, P10, O1, O3	Short training time, lack of updated training content, and poor attitude to work.
T1 Equipment failure	O4	Ageing, malfunction, and failure to update experimental equipment in a timely manner.
T2 Impracticable or restricted Operation	H5, T1	Inappropriate experimental design, presence of obstacles.
T3 Incomplete regulations	O4	The situational conditions exceeded the boundaries of regulations.
O1 Ineffective skill training	O4	Lack of practical training, short training time, or insufficient training intensity.
O2 Ineffective knowledge training	O4	The training content had not been updated, there was no training, and the training time was insufficient.
O3 Ineffective safety education	O4	Tutors did not emphasize clearly on safety awareness, and students did not attach importance to it.
O5 Excessive demands	O4	Multiple tasks, temporary tasks.
O6 Irregular working	O4	Nighttime experiments

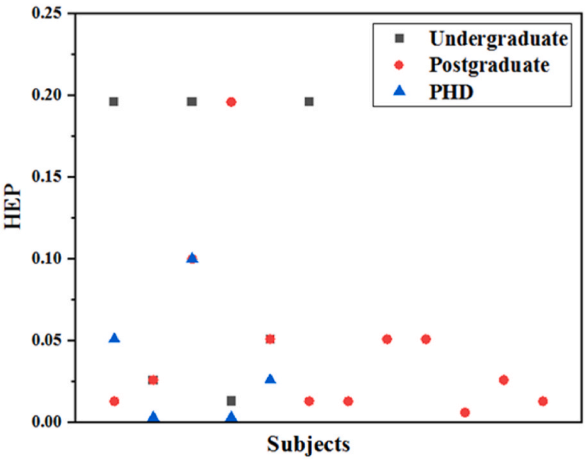

Fig. 4. HEP scatter points relating to the target position of the participants.

Table 22
The calculation results under assumption.

No.	Education	Total weight factor for CPCs = 1	Total weight factor for HIFs = 1
Subjects 1	Postgraduate	0.00162	0.051
Subjects 2	Postgraduate	0.00325	
Subjects 3	Postgraduate	0.013	
Subjects 4	Undergraduate	0.0258	
Subjects 5	Postgraduate	0.0258	
Subjects 6	Postgraduate	0.00649	
Subjects 7	Postgraduate	0.00162	
Subjects 8	PHD	0.00649	
Subjects 9	Postgraduate	0.00162	
Subjects 10	Undergraduate	0.00325	
Subjects 11	Postgraduate	0.00649	
Subjects 12	Undergraduate	0.0258	
Subjects 13	Undergraduate	0.00162	
Subjects 14	PHD	0.0004	
Subjects 15	PHD	0.013	
Subjects 16	PHD	0.0004	
Subjects 17	Postgraduate	0.00649	
Subjects 18	Undergraduate	0.00649	
Subjects 19	PHD	0.00325	
Subjects 20	Postgraduate	0.0008	
Subjects 21	Postgraduate	0.00325	
Subjects 22	Postgraduate	0.00162	
Subjects 23	Undergraduate	0.0258	

Data curation, Formal analysis, Software. **Min-Jun Peng:** Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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