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Evaluation of an Immersive VR-based Chemical Production Safety Learning Using a Transferable Psychosomatic Approach*

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Considering effective transfer of knowledge and skills in chemical production safety, virtual reality (VR) technology is adopted to build training platform of safety operation. This study focuses on shortening the breach between the highly demanded human-machine interactions and the learning approaches utilized in process engineering by experimentally evaluating the effectiveness of different learning approaches in an image-based unusual state. The trainees' performance are assessed through quantifiable measures, learning efficacy and performance, used for the specific objectives. The result reveals that testable training in VR for complicated safety-specific activities is not statistically different from the conventional lecture mode. But VR learning shows an appreciable positive enhancements in participants' perceptions of entire learning and their existence on task during the training. Also, it reveals that the knowledge retention rate of video-based lecturing can be over-valuated if left unchecked. The positive results of this method lie in improving the dependability, reducing damage costs and enhancing safety performance in chemical operation process.

Keywords: process engineering; immersive environment; simulation of operation learning; methodologies of learning and evaluation; chemical safety education

1. Introduction

Manufacturing process is changing in chemical industry [1–3]. As firms in the industry improve process efficiency and safety through effective data collection, funding for digital development is estimated to reach $320 million by 2022 [4]. Meanwhile, a survey of accidents in chemical manufacturing fields is published [5], indicating that accidents of chemical manufacturing have occurred in many countries. There are several main phenomena revealed in Bhopal disaster [6]: unqualified chemical awareness, inadequate filed maintenance, and delayed emergency response resulting in massive chemical spills leading to significant injuries and deaths.

Chemical manufacturing processes are filled with highly demanded human-machine interactions that are usually connected to automated schemes including messages that have various tiers of dependability. There have seen the excellent achievements in scientific research in different fields of the process engineering in recent years, such as renovation design, reinforcement, optimization, and advanced instruments, etc. With this progress, the complexity of the human-machine interface has increased significantly. Meanwhile, there are several properties, e.g., extensive, distributed, dynamic and complex, in chemical processes. In practice, some site tasks are conducted through operators, engineers, and various functional teams [7]. Hence, the character and importance of human mistake in process engineering has received increasing attention over the past 10 years [8–10]. There are several types of concern for process operators involved e.g., concentrated, partitioned, and selective concern are needed during typical manipulations [11]. Process operators, in other words, have to allocate their concern strategically in accordance with the different scenarios or conditions. Operators are bound to encounter a variety of challenging topics for unusual states [11].

Regarding the learning modes in chemical manufacturing industry, traditional learning approaches and operation simulators are usually applied for operator's training in chemical factories [12]. Because the activities are more complicated, it has already been manifested that such situation

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leads to trainees not involving and easily complying with processes by rote [13–16]. Due to the lack of authenticity and realism in these approaches, they do not reach the best effect of learning and understanding for the trainees. This has leaded to strategies to offer safety instructions ahead of actual task. Nowadays, Chemical safety education evolves with the progress of multi-media technology. By utilizing the features of immersive virtual reality (VR) technology in chemical manufacturing process, operators can achieve better comprehension and operation performance if unusual states occurred [17]. Once an unusual state is found, an issue-to-be-resolved is developed and the requirement to re-scheme for the state becomes important. Operators should manifest techniques for discovering problem and quick re-scheming strategies to deal with an unusual state. Furthermore, several researches [18-20] depict the notion and advantages of utilizing VR for disciplining the operators in process engineering to overcome the above-mentioned obstacles. In an immersive VR environments, the specific cases can be easily simulated, e.g., anomalous conditions, accidents and start-up/shutdown of process. Several times hence promoting the operator's knowledge and skills [20].

The target of this research is to experimentally comprehend and assess the performance of trainees under specific unusual states, which is demonstrated in a 3D VR settings. The evaluation of trainee's perception and performance are on the basis of proposed questionnaire of learning efficacy and key performance indicators respectively. In addition, this assessment is also compared regarding two different learning approaches (i.e. a typical slide-based lecturing and an immersive VR-based settings) that are applied during the learning stage of the experiment. This research is outlined below: The second section depict the relevant researches. The third section presents the experimental method and its key issues. The fourth section depicts the experimental results. The discussions and implications are mentioned in the fifth section. Eventually, the conclusion and relevant follow-up work are provided in the sixth section.

2. Background and Relevant Work

The development of educational methods based on VR technology has become extremely popular in the past decade. For example, a simplified educational approach is proposed for a practical VR course in engineering education [21]. This task proposes approaches and tools for establishing VR courses, but ignores the stages related to modifying the created courses to the needs of the environment to be simulated. The utilization of VR in the learning loop, which involves the establishment of architectural elements, is presented [22]. The depicted simplified approach is devoted to one sort of solution, namely architectural design in city's construction. A new approach [23] is proposed for the establishment of courses on the basis of virtual learning plant. The presented solution is specific to learners and is chiefly restricted to courses devoted to reconfigurable fabrication. An educational method is proposed [24] to the utilization of VR in learning and the assessment of learners' creativity. Likewise, an educational approach is proposed [25] to create professional skills utilizing a VR settings. It addresses a new pattern SMART hybrid lab creation pattern that can be approached methodologically. It defines five basic phases that permit the execution of VR in the learning procedure. This approach is aimed at the scholastic settings and can be smoothly applied to supply the educational procedure of learners. The above VR-based education methods applied to different fields of literature provide great insight into the approach of chemical production safety education in this study.

Meanwhile, the chemical safety field has applied VR technology in recent years to three aspects: safety of laboratory, operator's learning in factory safety, chemical education for future engineers.

2.1 VR-based Safety Education in Laboratory

VR technology is mainly aimed at developing a hazard-free settings where learners can get authentic training before operating practical tasks to promote their experience. The whole procedure and its steps are simulated by animations to construct an immersive perspectives. It is very beneficial in training the processes that include caustic chemicals and the emission of toxic substances. Moreover, the learners can experiment in a safe settings as frequently as needed, which would otherwise impossible because of the cost of materials [26]. The effect of packaging design in the learner's sensation regarding the riskiness of packaging involving chemical materials has been achievable by using the virtual reality technology [27]. The outcomes from the feedback of questionnaire reveal that users can make decisions upon the familiarity and riskiness of the package shown in virtual environment. This research emphasizes VR can be applied to estimate the package design to elicit user's behaviors.

A MR (mixed-reality) platform is generated to discipline trainees on several chemical experiments. This research reveals how operator performance can be enhanced through a properly virtual settings that concerns user requirements, e.g., pressure of time limit, interest, fidelity and perceived physical stress [28]. Meanwhile, a VR-based glove hygiene is created to train learners in introductory chemistry experiments [29], students can utilize hand operations for executing the steps in the virtual state. The result signifies the experience supported prepare learners for laboratory safety. A web-based virtual experiment system is developed [30]. By combing task points with instructing materials, e.g., slides, videos and interactive puzzles, to support learners. A positive correlation is found between the participants' exam results and their response in virtual experiment settings.

2.2 VR-based Safety Operation in Factory

In the field of chemical manufacturing, VR is mainly aimed at creating 3D immersive settings for promoting operator's skills and ability of emergency responses. A learning simulator of fired heater with VR mode is developed to discipline the operators in fluid industry [31]. This procedure is composed of two portions: the manner for igniting a fired heater and instructions for using VR tools. Eventually, a performance evaluation of trainees when they ignite the device in the virtual settings. A cognitive learning unit of oil depository is constructed to offer users with a trimetric 3D viewpoint of the whole equipment [32]. The unit also involves learning mode of emergency response with different abnormal situations in the virtual settings, such as fire accident, oil and gas leak, etc. A VR-based training of emergency response is generated in gas power factories [33], there are several items evaluated, including the effectiveness of learning, ergonomic feasibility and situational perception reached with Virtual learning. The conclusions indicate that a high grade of situational perception is offered by VR learning to the trainees. Besides, it is negligible due to the discomfort caused by the simulator is minimal, revealing its ergonomic feasibility.

Several researches are devoted to compare the influence of conventional approaches with VR-based methods in transfer of knowledge. The training efficacy is evaluated about conventional and VR-based modes respectively for learning mCDI operations [34]. The experiment group adopts relevant figures, piping and instrumentation diagrams and the control group uses virtual mCDI module. Learning effectiveness are analyzed applying questionnaires relative to the several key items, e.g., specifications of equipment, procedure of operation, and production. The result reveals that the total scores of the control team is lower than that of the experiment team. Concretely, the trainees in experiment team achieved noticeably better than the trainees in control team for recognizing different process facilities during the mCDI production. In addition, the researchers mention that the trainee can identify the sort and position of various process facilities in a complex procedure, e.g., mCDI, can be quite promoted by permitting them to inspect components in virtual environment. Furthermore, VR effectiveness is explored for emergency response in chemical leak [35]. By evaluating the operator's actions and the reaction speed to a simulated event in chemical factory, discovering the learning scores produced by two different learning methods. There are two portions examined in reaction of chemical leak: perception of personal protection and procedure for handling incident. The results are then offered as reference to the operators for perceiving their learning progress. The conventional and VR-based two modes are applied respectively in the task-specific training [36]. Several indexes are evaluated: system usability, perception and confidence of learning, feeling of presence and trainees' opinions. Trainees in the experiment group had a higher degree of confidence and presence in performing safety tasks than trainees in the control group. Even though the two groups are comparable in terms of task knowledge, the group that has received VR training feel more confident in utilizing relevant knowledge.

2.3 Safety Education with VR Mode in Chemical Engineering

To eliminate the breach between theoretic knowledge and realistic utilization, VR is useful and beneficial tool in safety education of chemical engineering. It can create a realistic environment where inexperienced learners can have a realistic experience based on practical industrial skills. A virtual chemical factory with a guided instruction of hazardous fields is constructed, e.g., inside of the reactor [37]. Besides, there are several accident situations in virtual laboratory generated to show the results of violating to safe rules in laboratory. Furthermore, VR is used to train students regarding the manipulation of a chemical factory [38]. There are several chemical facilities included in this virtual settings, such as pumps/valves, piping, reactors, etc. The participants can manipulate them to obtain an operation experience and understand the corresponding functions. A questionnaire with five indexes (necessity, difficulty, accessibility, usefulness and authenticity) are developed to evaluate the students' performance. The conclusion indicates that trainees strongly consider that operating on a virtual platform was more convenient than conventional mode. Two different groups (students and engineers) are evaluated for learning the understandings of chemical engineering in immersive VR-based games [39]. The results are revealed as follows: (1) intent of behavior to apply VR is higher for engineers than pupils; (2) compared to the traditional mode, pupils prefer VR due to its enjoyability and usability; (3) engineers are more interested in usability and feasibility in the utilization of immersive VR; and (4) most of participants consider that immersive VR gives a better training experience.

In short, VR technology is applied in various domains of chemical engineering to promote trainee performance and safety awareness. Although several studies have been conducted to compare and discuss traditional and VR two learning modes, the evaluation of VR efficacy is still on the basis of questionnaires and subjective responses. Evaluation of cognitive behavior is rarely considered. Besides, few studies evaluate VR efficacy compare with its equivalent actual settings. Therefore, it is essential to evaluate VR effectiveness systematically and its influence on human issues.

3. Proposed Workflow and Experimental Method

To concentrate the developments of safety learning in a chemical production settings depicting main accident hazards, the authors cooperate with safety and health specialists at DongDa Synthetic Chemical Co. Ltd. (DDChem) in Yongjia, China. This firm produces resin jewelry accessories, plastic plating buttons, resin buttons, and other products. Applying a complex, safety-crucial chemical production activity of extensive significance as a case investigation (unsaturated polyester resin, UPR). The dangerous facilities are reproduced in the factory by VR technology to offer self-directed and immersive safety learning. In this study, the real case is adopted to carry a complete quantitative evaluation of the cognitive behavior theory of the presented VR safety environment compared to the conventional learning mode. The main outcome of this study is an experimental methodological scheme that can be used to formally evaluate a learning activity with VR mode. The procedure of experiment is shown in Fig. 1 and the related details are depicted below.

3.1 Depiction of Course

This course, Safety Production Inspection and Monitoring (2 credits/36 class hours in total), is part of the chemical program for undergraduate students who pursuit a bachelor's degree in chemical engineering. It is an elective senior-level capstone course. To study this course, three prerequisite courses must be completed and passed, Introduction to Chemical Engineering, Unit Operation and Organic Chemistry Experiment. Meanwhile, this course is composed of three modules: Production Engineering, Safety Education and Safety Enforcement. This experiment is designed to focus on Safety Education modules.

Constructing a VR system for DDChem UPR production process provided the chance to settle two core safety-related objectives: (1) the authors expect that a contextual safety learning mode would improve present slide-oriented approaches applied regularly by manufacturing safety workers. In this manner, VR would enable participants to take an immersive navigation of the hazardous workplace and steer SOPs in an interactive way, avoiding any triggers for skimming, loss of focus, or suffering

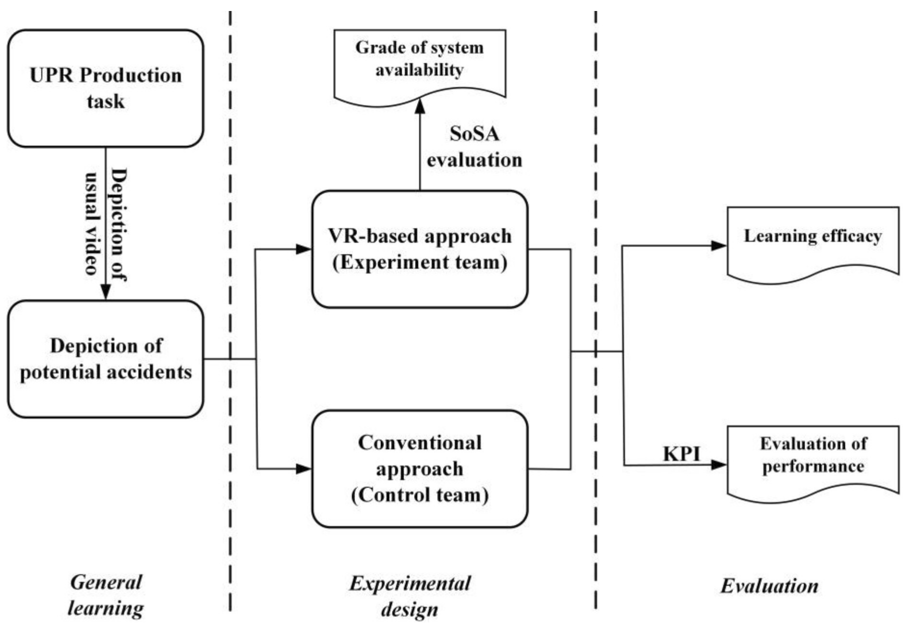

Fig. 1. Diagram of experimental procedure in chemical safety learning.

unnecessary loss of message retention; (2) Trainees can learn on their own off site through a VR learning platform before imperative and resource-intensive fellow learning on scene. This pre-learning method with immersive mode would hence reveal the chance for participants to obtain familiarity and self-confidence in their hazardous tasks before starting the hazard of learning in the real production scene.

To assess participant's achievement of learning objectives, there are two portions examined: learning efficacy and task performance (see Appendix A). The former evaluates the learning effectiveness and experience of UPR production process safety training. The latter assesses the emergency response capability for hazardous events. The details will be explained in the subsequent sections.

3.2 Sample

Twenty-nine samples, 25 of whom are male and between the ages of 20 and 22, participated in the Safety Production Inspection and Monitoring course. The samples are junior/senior undergraduates studying at Zhejiang College of Security Technology, China. Meanwhile, all participants have learned the fundamental knowledge of chemical engineering and equalized the technical understanding, i.e. the evaluation of the prior knowledge revealed no significant differences among all participants. Finally, all trainees are divided into two teams equally and randomly: Control Team (CT) and Experiment Team (ET).

3.3 Depiction of Working Scenario and Abnormal Situations

During the production process, a site operator works together with an engineer responsible for the production equipment at the monitoring room. They cooperate to execute a series of complex tasks, e.g., zone clearance, check of temperature and feeding volume, preparation of PPE (personal protective equipment), valve control, and connections with supervisor. In short, the UPR production task at DDChem factory is an extremely complex process that reveals clear hazards for poor mixing effect or unsuitable feeding speed in the reaction stage, a great accident to site workers, harm to the regional residents and the living environment.

The experiment to be evaluated is on the basis of the UPR production process that is composed of five stages: preparation, feeding, reaction, dilution, and tanking. Fig. 2 shows the conceptual flowchart of UPR production process. The brief depictions of whole process are listed below.

In the Preparation stage, the operator puts on full body protective equipment (protective clothing, gloves, mask), then the operator touches the static elimination device with his gloves to eliminate the static electricity from his full body. Next, in the Feeding stage, the Dihydric alcohol is fed the reactor, raise the temperature to 100 °C, and then put the material Diprotic acid into the reactor. In the Reaction stage, the polycondensation reaction (also called Polyethylene terephthalate) is occurred between Dihydric alcohol and Diprotic acid in the reactor, raise the temperature and keep it between 170~200 °C, add inert gas during the temperature rise to produce unsaturated long-chain polyester molecules. By lowering the temperature and keeping it between 60~85 °C (in the Dilution stage) the condensation product is diluted through Styrene and dissolved into unsaturated monomers to a viscous liquid, which is the UPR product. In order to prevent the UPR from cross-linking and curing before use or during storage, a Polymerization inhibitor is added to the UPR. Eventually, the tanking process will not take place until the tem-

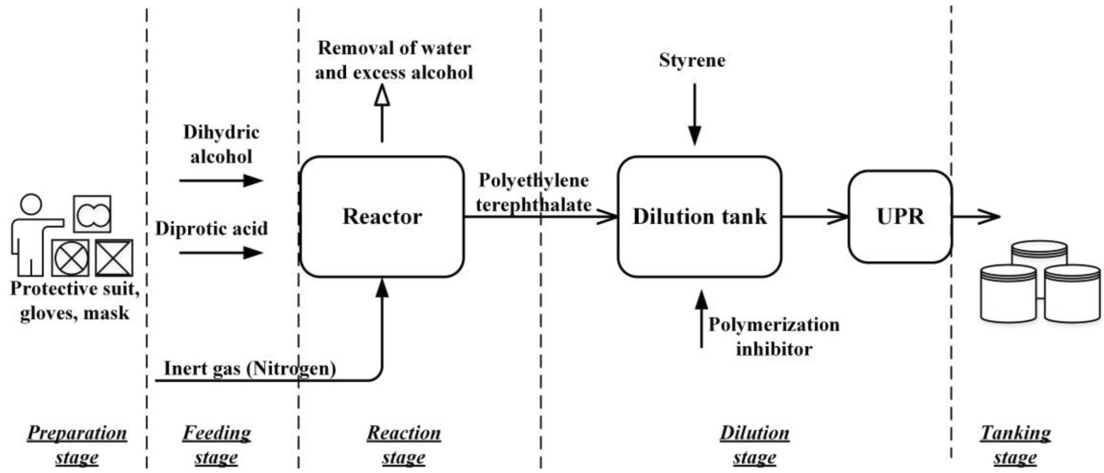

Fig. 2. Conceptual flowchart of UPR production process.

Table 1. key parameters and outcomes of each stage in UPR production process

Stage	Parameter/Element				Outcome	Thermal state
	Pressure (Mpa)	**Reaction temp. (°C)**	**Reaction time (min.)**	**Reactants**	**Products**	**Exothermic or Endothermic**
Preparation	0.1	30	30min			
Feeding	≈ 0	100	30min	• Dihydric alcohol • Diprotic acid		Endothermic
Reaction	0.16~0.24	170~200	480 min.	Inert gas	Unsaturated long-chain polyester molecules	Endothermic
Dilution	0.1	60~85	60 min.	• Styrene • Polymerization inhibitor	UPR	Exothermic
Tanking	0.1	Below 40			UPR	Exothermic

perature drops below 40 °C. As for the key parameters of each stage (e.g., pressure, reaction temperature, reaction time, etc.) and the related products and thermal states, they are summarized in Table 1.

The related details of each stage are depicted in Table 2. As for the main abnormal situation and its corresponding accident in each stage, they are revealed in Table 3 and Fig. 3. Once any of these abnormal situations occurs, the operator should immediately notify the incident to the engineer at monitoring room. At the same time, the operator also needs to handle this event (e.g., adjusting the valve opening, controlling the vacuum pump, etc.) and report the results. In the event of a situation that the operator cannot handle, such as a fire or explosion, the operator must contact the monitoring room, and the engineer will submit fire-fighting and rescue requests to the fire department of factory.

3.4 Architecture of the Proposed VR System

Fig. 4 shows a conceptual diagram of the proposed VR framework. The server portion deals with the demand from the user and conduct the processes of VR scene. A scene process conducts a virtual settings and the users, which are linked the scene. Each user has his/her own program, conducting the network junction and data deliver applying the plugins and the multiplexer. For each entity kind that can be transferred to the end user there is a plug-in. If the virtual settings, for example, is composed of textured menu, there would be a plugin for transferring the menu and a plugin for transferring the textures. Each plugin generates a data flow that is integrated through the multiplexer to one data flow. The multiplexer is capable of transferring menu and texture at approximately the same time. For easier access to the data of the virtual environment, the multiplexer and the plug-ins have to be depicted through threads. In the end

Table 2. Brief depiction of each stage in UPR production process

Stage	Brief depiction
Preparation	This stage is for the operator to confirm the safety and protection work before the UPR production process. First, the operator puts on full body protective equipment (protective clothing, gloves, mask), then the operator touches the static elimination device with his gloves to eliminate the static electricity from his full body. In addition, it is also confirmed that the eyewash and shower equipment are working properly.
Feeding	Firstly, transfer the material liquid to the reactor by turning on the transfer pump, and then turn off the transfer pump when the target liquid level is reached. Next, inject heat-conducting oil into the jacket embedded in the reactor and turn on the mixer for stirring. At the same time, loosen the screw of feeding baffle, remove the baffle and the feeding port will appear. Then pour the granular material from the feeding port into the reactor to the specified quantity, then reset the feeding baffle and finally lock the screw.
Reaction	This stage is the core of the whole production process. When the reactor is warmed up to 200 °C (about 4 hours), turn down the flow of heat-conducting oil valve to the specified range, and then keep it warm for 2 hours. Then, turn on the vacuum pump to pump out the air from the reactor to the standard value and turn off the vacuum pump. Then, after closing the heat transfer oil valve, open the cold oil valve in order to inject cold oil to let the reactor start to cool down to 150 °C (about 1 hour), and finally close the mixer.
Dilution	Add the phenacetin and auxiliaries to the dilution kettle through the transfer pump, and turn on the mixer for stirring at this time. Turn off the pump when the amount of phenacetin and auxiliaries has reached the required quantity. Turn on the vacuum pump to pump the material and control the temperature not to exceed 90 °C, also turn on the cooling water switch and let the cooling water inject into the dilution kettle. Turn off the vacuum pump and mixer when the material has been pumped. The pumped material is tested for viscosity, and if it meets the standard, the discharge valve of the reactor is opened for material output.
Tanking	The standard UPR is output from the discharge valve of the reactor, then filtered through the filter bag to filter the impurities and injected into the tank to reach the specified weight to complete the tanking process.

Table 3. Depiction of main simulated abnormal situations

Stage	**Depiction of the abnormal situation and its potential hazard**
Preparation	Failure to wear personal protective equipment (PPE) or eliminate static electricity operation, so that when there is a material vapor leakage, the energy generated by static electricity may cause a fire or explosion (as illustrated in Fig. 3(*a*)).
Feeding	Failure to use the vacuum pump properly allows air to enter the reactor, causing the air to mix with the vapor inside and form an explosive gas mixture (as shown in Fig. 3(*b*)).
Reaction	Unsuitable feeding speed or poor mixing effect may lead to flushing accidents, which in turn may cause major accidents such as fire, explosion (see Fig. 3(*c*)), scalding or poisoning.
Dilution	Improper adjustment of the reactor feeding valve switch and dilution of the cooling water in the jacket of the kettle resulted in the optimum temperature of the resin synthesized by polyester and phenethyl coin exceeding 80 °C. When the temperature reaches 85 °C, the styrene self-polymerization effect will be occurred (Fig. 3(*d*)).
Tanking	If the material tank is dumped, it will lead to human injuries and material loss, and if it encounters an ignition source, it may cause combustion (as shown in Fig. 3(*e*)) and then cause an explosion.

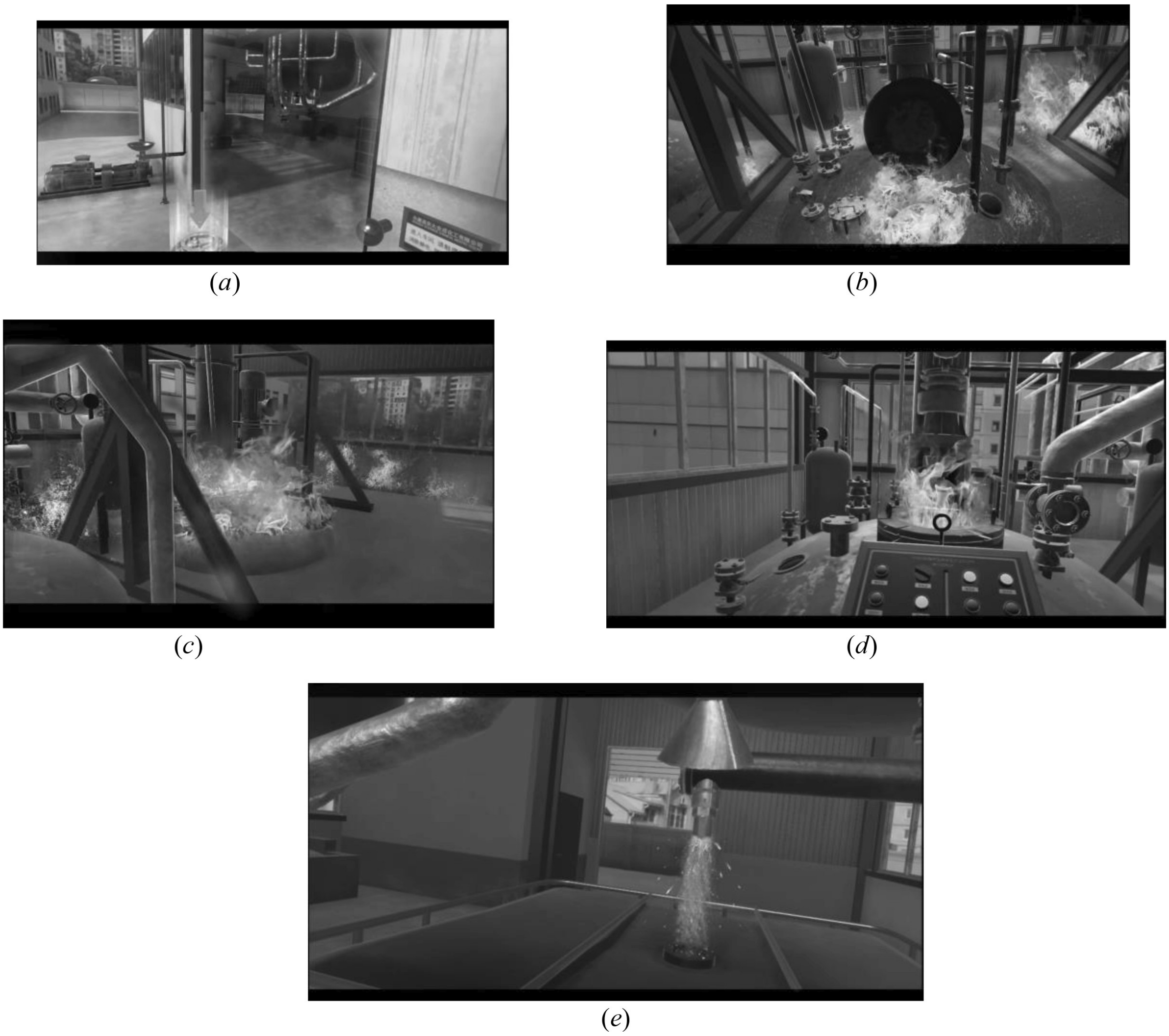

Fig. 3. The VR scenes of accident in each stage: (a) no wearing PPE -preparation stage, (b) an explosive gas mixture – feeding stage, (c) explosion – reaction stage, (d) self-polymerization effect – dilution stage, (e) a combustion – tanking stage.

user (client portion), a process conducts several portions, including the demultiplexer, the plugins of client, and the connection of network. The incoming data flow is demultiplexed and assigned to the corresponding plug-ins to obtain the initial data entities. Thereafter, applications using a client/server architecture are responsible for visualizing or processing data objects.

Meanwhile, there are several information included in relational database: (1) entity models in virtual settings; (2) files archived in the storage; (3) data of voice prompt mode and self-practice

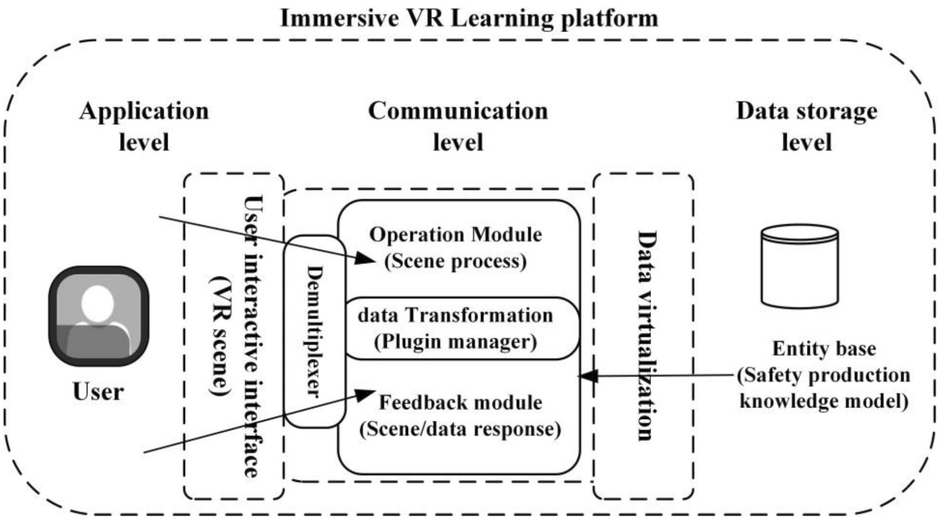

Fig. 4. Diagram of the prototype VR architecture.

mode, for instance, audio-type repository, records of message, and so on; (4) scenes and layouts for safety practice process. The shared data can be stored in a file set in the database server or in the corresponding relational database. A single application server executes the application logic, which coordinates between shared data and performance (user scene and server), and conducts the shared data. It accepts demands from the user via remote approach invocation and a general portal interface modes. The share data from the application logic in answer to queries via SQL schema. Furthermore, the participants can communicate by the virtual settings.

3.5 Procedure of Learning

The curated messages are provided to all trainees, the topics are: (1) the objectives of learning; (2) a performance evaluation and safety statements of the learning activities included; (3) introduction of UPR production process; and (4) a video explanation to potential accidents. In Team A (CT), 15 trainees are needed to finish the conventional learning method with image modes (e.g., videos, pictures and slides, etc.) regarding safety education in the UPR production task. These contents truthfully recreated existing image-based DongDa Synthetic Chemical (DDChem) training materials, with aside exposition guaranteeing an identical experience for all trainees in this team. On the other hand, in Team B (ET), 14 trainees use the interactive learning approach with immersive VR mode for safety training of the UPR production procedure (as shown in Fig. 5). All trainees are asked to learn for 80 minutes per week for a total of six weeks. Meanwhile, they are permitted to look into the essential learning materials once only.

3.6 Analysis of Learning Efficacy

Trainees are asked to fill out several questionnaires with tested validity to assess their learning efficacy. The details are depicted below.

3.6.1 Learning Effect in Specific Events

Trainees' post-learning knowledge of the UPR production activity is evaluated in a paper-pencil exam constructed of five event-specific open-ended questions, proposed by two authors and a DDChem safety manager. These questions are on the basis of the learning materials and related grading regulation at DDChem. The exam papers are marked by blind review, the referees are unaware of trainees' information, e.g., gender, status, team. Furthermore, tests are evaluated by the three referees (a DDChem safety manager and two research members), applying DDChem score-based marking mode. By summing up the test

Fig. 5. A trainee performs the UPR production process with an immersive VR mode.

scores and averaging them, the final percentage mark for each trainee is acquired.

3.6.2 Learning Experience

Trainees' perceive that the entire training experience is also important. It is different than learning efficacy on an exam [40]. Trainee's experiences are evaluated by using six customized statements, which are specially created for the evaluation of two learning modes. Every trainee grades his/her perception with these narrative questions on a type of psychometric response scale, five-point Likert scale. Questions consider perspectives of the training experience that are indexes for efficacy, e.g., the sense of gaining task-related knowledge and the utility of the learning approach in the specific event and otherwise, and the confidence acquired to implement safety-critical activities alone later.

3.6.3 Perception of Existence

This term, existence, can be explained as the depth of the "immersive" feeling trainees imagine they are experiencing as they interact with the learning media. It is related to, but not same to, the somatic immersion created through the technological devices that host the experience. Despite there is no consistent conclusion on the impact of the learners' perceived existence in a virtual settings on learning [41–43], immersion has been revealed to support improved work fulfillment, knowledge, and techniques promotion inside and outside of virtual learning settings [44–45]. In this study, a questionnaire of multi-media presence [46–48] is adopted to quantify the participant's psychological engagement inside a learning settings. Trainees respond their degree of agreement with a series of descriptions, utilizing a response scale in five points. In general, there are four factors captured in this measure: actuality, perception of real space, harmful sense and involvement. Table 4 shows the terms and their corresponding definitions.

3.6.4 Availability of System

Regarding the phase of human-computer interaction (HCI) assessment, the Scale of system availability (SoSA) has become the domain criteria to evaluate the performance and applicability of system for the expected goals [49–52]. Ten comprehensive narrative questions are designed and then replied by every participant with his/her agreement level on a typical Likert scale. The result is formed a full score of 100 that can be transformed to a rank A-F. In this study, SoSA is applied to assess the subjective availability of the proposed VR learning platform.

To compare the ET and CT two teams in the three aspects of learning effect in specific events (Section 3.5.1), Learning experience (Section 3.5.2), and Perception of existence (Section 3.5.3), the Mann-Whitney U test is introduced, applying SPSS, to decide whether ET and CT are statistically significantly differences on the three computable items.

Table 4. Definition of key presence for evaluating a participant's engagement in the learning activity

Term	Definition
Actuality	Tend to sense that the learning content is true and lived-in.
Perception of real space	Sense of location and control over the real space.
Harmful sense	Negative influences bringing about involvement with the media.
Involvement	Tend to sense engaged in and be pleasuring the learning content.

3.6.5 Impression Analysis

To evaluate consistence between the outcomes acquired from the statistical analysis of organized investigation answers in above-mentioned subsections and the oral trainee response on their learning perceptions, focus group interviews (a kind of qualitative research) is adopted and transcribed the trainees' feedback into transcripts with text mode. Afterward, this text structure with word by word is parsed against the LIWC analytic tool [53–54], exporting a percentage of terms matching psychological identifiers. In this study, the percentage of terms tagged with adverse or positive impact are collected to allow for quantifiable comparison between the ET and CT response records.

3.7 Analysis of Task Performance

Key Performance Indicators (KPIs) is a quantitative evaluation of long-term performance against a defined target. It provides groups with goals, key features to measure the process, and intuitions to help members the whole enterprise make better decisions. KPI supports every field of the enterprise make progress in the strategy phase. Meanwhile, it also attempts to summarize and provide a multifaceted view of the factory through numerals or graphs, illustrating the dynamic reaction of the process to production changes and external disturbances. Even though a KPI is usually on the basis of the consideration of a few process parameters, its assessment is fairly easy through statistical approaches with multi-dimensional mode once these parameters are stored in a historical archives. In the event of participant evaluation, the performance indexes are related to participants' decisions and actions, and therefore to their complex behavior. To evaluate the trainees' performance in this study, the proposed KPIs are concentrated on the

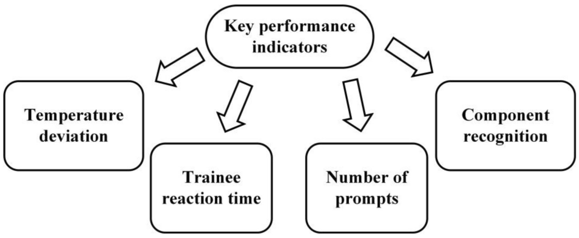

Fig. 6. The proposed KPIs for analysis of performance.

minimizing the effects of the assessed unusual state, which starts with the improper feeding of reactor by the operator. The key variables of dilution process (as illustrated in Fig. 6), which can define the severity of this event, are the trainee reaction time, temperature deviation, recognition of component and number of prompts.

4. Results

4.1 Brief of a VR-based UPR Safety Production Modeling

To develop the new learning scheme with present safety criteria, the authors integrate DDChem's typical lecturing materials, SOPs, and depiction of emergency measures into VR-based learning. The partial screenshots are illustrated in Fig. 7. A field configuration map is applied to realistically repre-

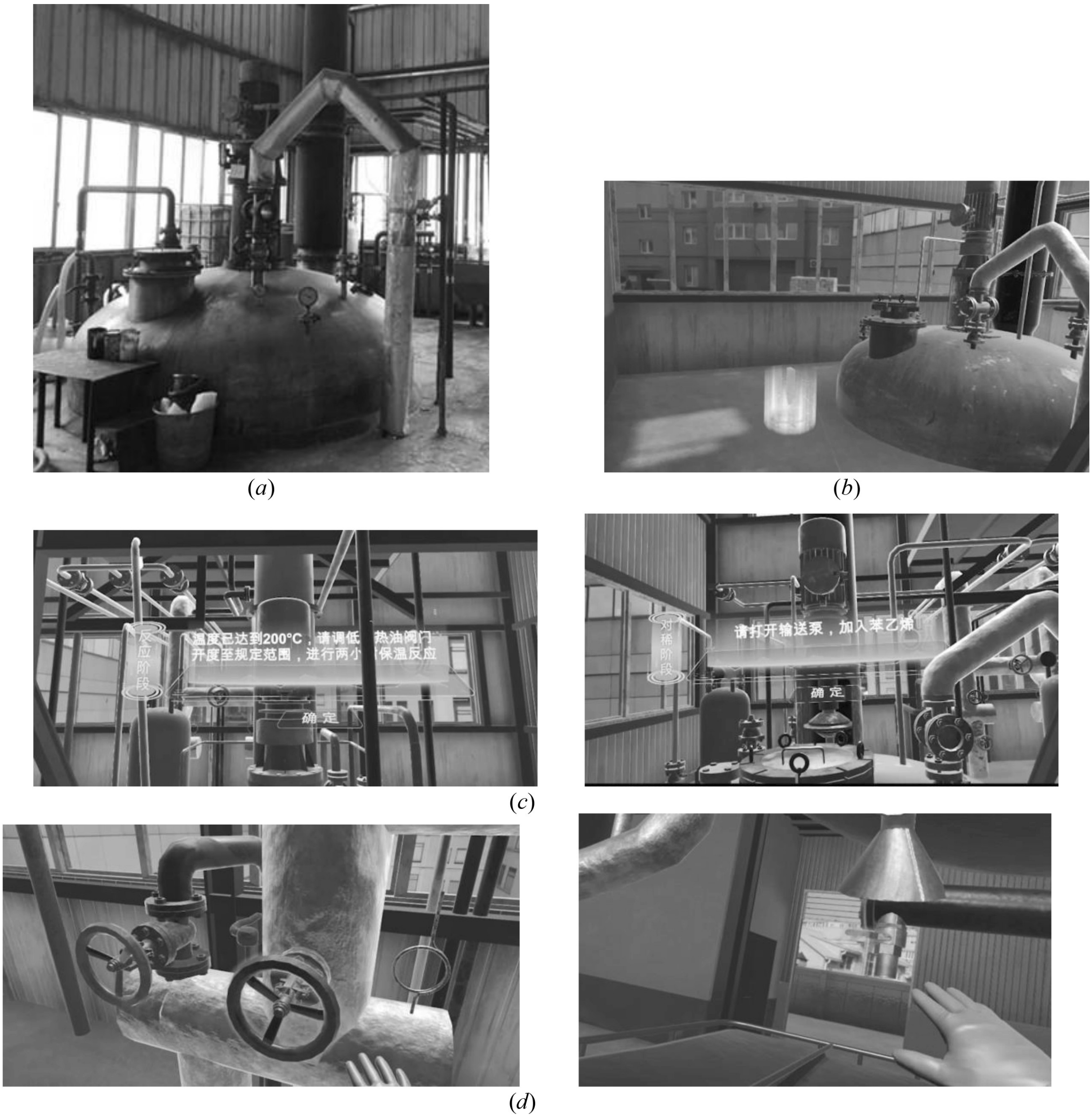

Fig. 7. The corresponding instructions in VR scenes: (a) the real scene in dilution stage, (b) the VR scene in dilution stage, (c) the instruction of task on a virtual panel, (d) a blinking aperture prompt highlighting.

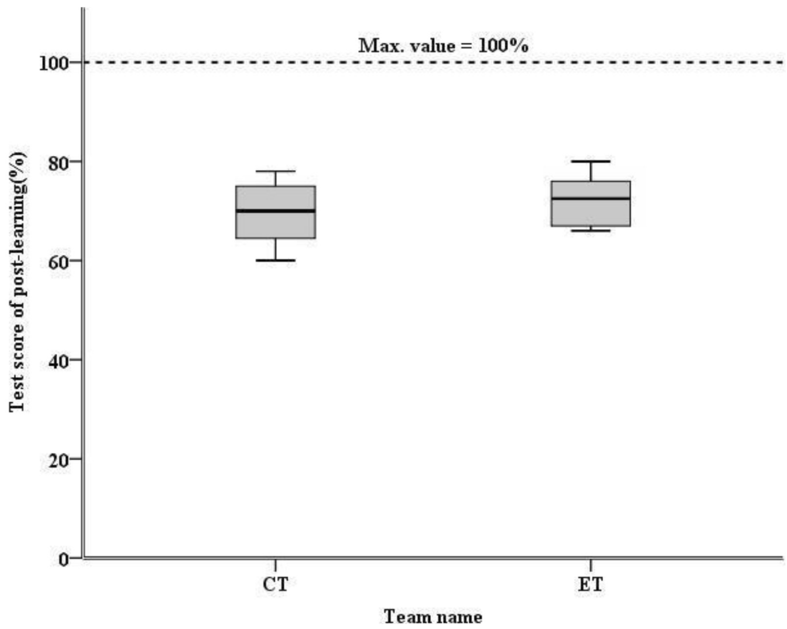

Fig. 8. The results of learning effect in specific events.

sent the geometry and topology of UPR production scene (as shown in Fig. 7(*a*), 7(*b*)). As for the related multimedia materials (such as audio, video, photo, etc.), they are embedded into the corresponding facilities and equipment in the production site. In addition, the pipeline and the other architectures are also constructed together. The virtual environment is exported into the Unreal Engine, where the HTC Vive kits (motion controller and HMD) are adopted to execute the various interactions that are needed all over the learning. The whole learning procedure are performed based on finite-state machine. The trainee has to complete the task correctly item by item, and when one task is not done, the next one is not allowed to perform. Meanwhile, the trainees can read the task instructions on a virtual panel in the center of the display screen (see Fig. 7(*c*)). Even if the platform does not provide any response related to the wrong trainee action, the trainee can ask assistance from the platform in the form of a blinking aperture prompt highlighting the position where the present activity step is to be performed (Fig. 7(*d*)).

4.2 Assessment of Safety Learning

Having generated a custom VR safety learning system for DDChem's UPR production process, the benefit of this new learning approach can be formally evaluated against DDChem's current learning modes. The key to this kind of evaluation is to carry together experimental methods that concentrate on mental rules that have not been usually applied in chemical safety learning evaluation. The relevant results are summarized and described as follows:

4.2.1 Learning Effect in Specific Events

Event-specific training for the UPR production process is evaluated applying a questionnaire created on firm learning contents and grading regulation. Comparing the test scores of the two teams, CT ($M = 69.9$, $SD = 6.12$, $Mdn = 70$) and ET ($M = 72.4$, $SD = 4.88$, $Mdn = 72.5$), the outcomes reveal that there is no significant difference $\{U(S\text{CT} = 15, S\text{ET} = 14) = 80, z = -1.095, p = 0.290\}$. Nevertheless, there is more compact interval around the mean for the ET compared to the CT, the result is illustrated in Fig. 8.

4.2.2 Learning Experience

Trainees' feel confidence of having obtained new knowledge is evaluated utilizing a questionnaire formed six questions, exploring diverse perspectives of the learning perception. There are three questions revealed significant differences between the learning teams: (1) Considered useful for other complex work $\{U(S\text{CT} = 15, S\text{ET} = 14) = 52, z = -2.68, p < 0.05\}$; (2) Considered useful to enhance decision $\{U(S\text{CT} = 15, S\text{ET} = 14) = 49.5, z = -2.98, p < 0.05\}$; (3) comfortable performing the work independently $\{U(S\text{CT} = 15, S\text{ET} = 14) = 61.5, z = -2.12, p < 0.05\}$. As illustrated in Fig. 9, trainees consider VR learning approach as having more possible than conventional lecturing for supporting learn in other complicated work and for enhancing the tips of decision-making. Furthermore, VR method also provides trainees confidence that

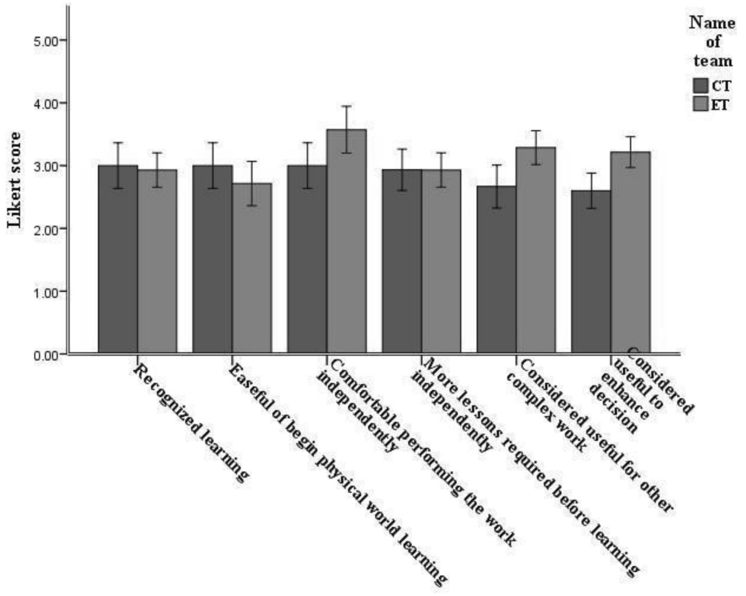

Fig. 9. The results of learning experience.

they can perform the work safely and independently. In general, trainees in the ET perceive more self-confident than those in the CT.

4.2.3 Perception of Existence

A questionnaire of multi-media presence is applied [46] to assess trainee's entire perception of learning settings across four core factors (as shown in Table 3 and Section 3.5.3). The outcomes reveal that members in the ET depict perceiving a higher sensation of existence than those in the CT. there are three elements found extremely significant differences between the learning teams: (1) involvement $\{U(S\text{CT} = 15, S\text{ET} = 14) = 9, z = -4.38, p < 0.001\}$; (2) actuality $\{U(S\text{CT} = 15, S\text{ET} = 14) = 10.5, z = -4.36, p < 0.001\}$; (3) perception of real space $\{U(S\text{CT} = 15, S\text{ET} = 14) = 28, z = -3.59, p < 0.001\}$. As for the harmful sense, although trainees in the ET depict perceiving a less harmful senses than those in the CT, the result is not significant difference (as illustrated in Fig. 10).

4.2.4 Availability of VR Learning System

A Scale of system availability (SoSA) [52] is

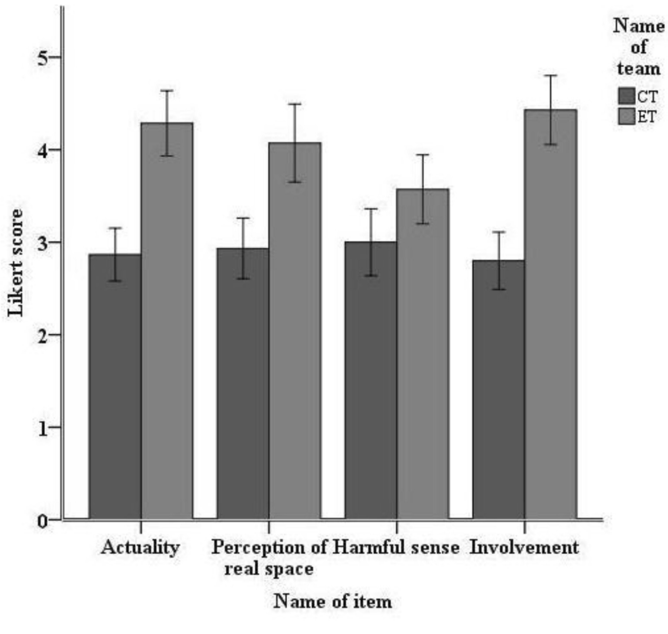

Fig. 10. The results of perception of existence.

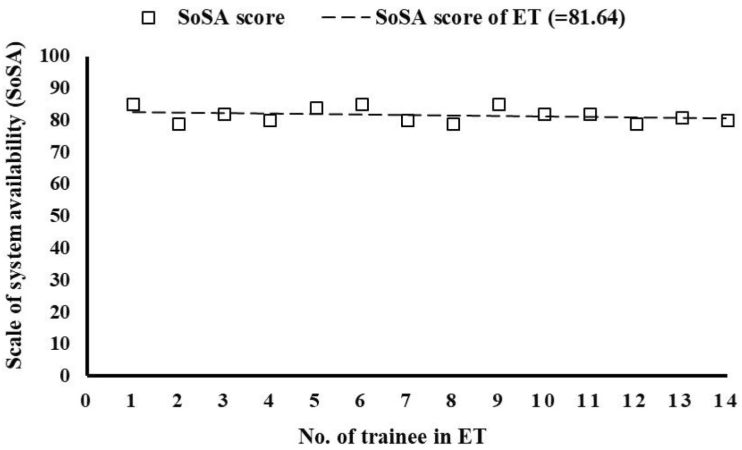

Fig. 11. SoSA score of the proposed VR system for ET.

adopted to measure the intuition, satisfaction level, and efficacy with which members can reach the work goals in the VR settings. The average SoSA score calculated is 81.64 (as illustrated in Fig. 11), which positioned the proposed VR learning system on the border of the top ten percentage of SoSA scores [51]. The outcome reveals a whole excellent perception for trainees in the ET. On the other hand, members are also inquired several questions (rated on a typical Likert scale) to explore their perception further in VR safety learning (see Appendix B). In short, the trainees in the ET very agree ($M = 4.82$, $SD = 0.52$) that they have acquired an adequate quantity of guides to help them all over their learning. Meanwhile, trainees perceive the VR experience are moderate ($M = 3.75$, $SD = 0.83$). They feel the simulation is smooth and steady ($M = 4.1$, $SD = 1.05$) as well as sharpness ($M = 3.9$, $SD = 0.74$). Finally, the hand-held interactions with the VR mode are perceived as relatively intuitive ($M = 3.85$, $SD = 0.95$) and the HMD is discovered to offer pleasing enjoyment during the learning process ($M = 4.03$, $SD = 0.78$).

4.2.5 *Impression Analysis*

To verify the formal statistical results, a quantitative analysis with open trainee response is introduced in this study. Utilizing text-based records of ET and CT member responses, the LIWC analytic tool [54] offers further intuition on the basis of emotive impression hidden in plain transcript. Compared to CT (2.4% of the image-based learning response collection), more positively emotional terms are used in the ET (4.5% of the VR learning response collection). The related outcomes are shown in Table 5.

4.2.6 *Performance of Task*

During the experiment, prompts are offered and kept consistent for all the trainees. It acts as a function of participants' actions. If the trainee, for example, find himself lost in the VR settings, then the trainee is suggested to go forward the specific scene. This prompt is provided after a constant interval of time to keep the consistence among experiments. Fig. 12 illustrates the number of prompts provided between the learning teams; the trainees of CT are more than those of ET. Another key variable to evaluate the trainee's performance is the temperature deviation. Smaller temperature deviation shows a quicker response of the trainee (i.e. trainee reaction time) in detecting and responding the state to the engineer, who afterward adjusts the valve to eliminate the abnormal heating. Consequently, smaller temperature deviation reduces the risk of fire, explosion, and possible harms to the reactor and its surrounding equipment. The final temperature deviation, therefore, is assumed to correlate closely with the reaction time of each trainee of each team. Fig. 13 shows that the average

Table 5. LIWC analysis of text-based transcripts for participant responses

Parameter	Definition	Team	
		CT	**ET**
Number of terms	Number of terms in the transcript	1167	964
Emotive pitch	Terms in positive and negative two ways (it means negative pitch if the result is less than 50)	25.3	87.5
Emotion with positive pitch (%)	Positive terms (such as like, great, smooth, etc.)	2.4	4.5
Emotion with negative pitch (%)	Negative terms (such as difficult, unclear, dislike, etc.)	3.1	1.4

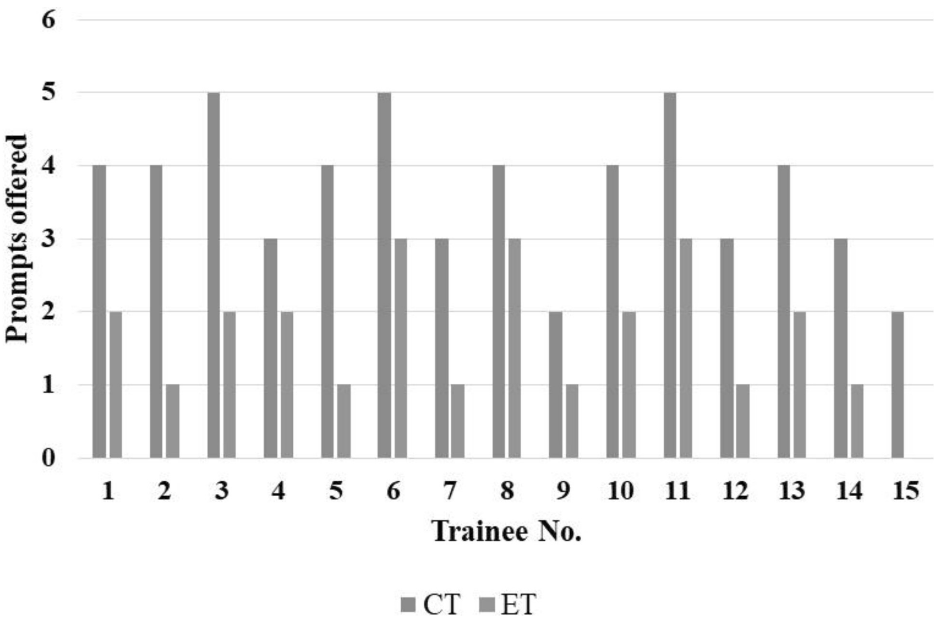

Fig. 12. Number of prompts provided to each trainee.

temperature deviation caused by the trainees of ET (M_{TD} = 1.98 °C, M_{RT} = 2.97 sec) is smaller than that in the CT (M_{TD} = 3.82 °C, M_{RT} = 5.82 sec). As depicted in Section 3.3, the operator is asked to adjust a specific component at the final step for handling abnormal situation. The trainees in the ET are higher achievement rate in recognizing the correct component as compared to those of CT and the results are shown in Fig. 14. Overall, these previous outcomes reveal how a learning approach on the basis of immersive VR modes permits achieving a state perception and process comprehension that are obviously higher than those acquired through typical learning ways. The indicators depicted quantify the benefits of a learning method with immersive VR environment and its

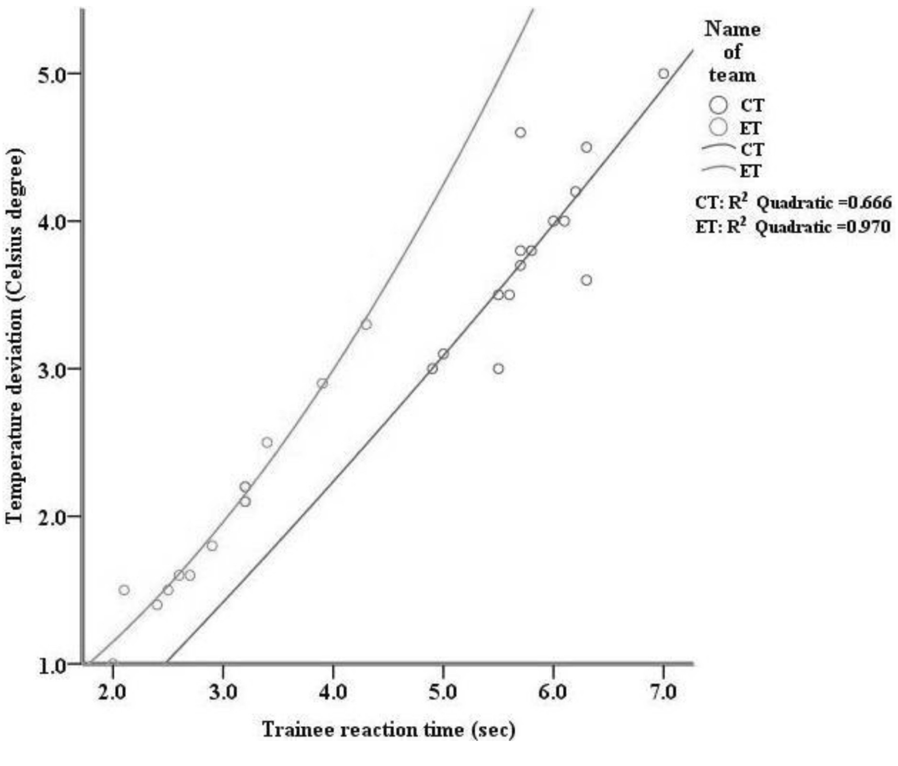

Fig. 13. Mean temperature deviation during experiments for two teams.

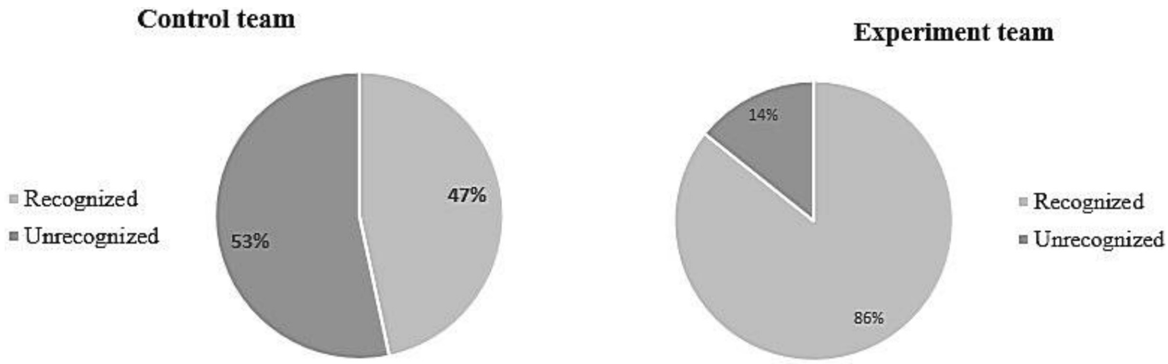

Fig. 14. Comparison of component recognition by the trainees in CT and ET.

positive responses on the evaluation of production site operators.

5. Discussion and Implication

Using the proposed approach of transferable psychosomatic evaluation, the analysis of statistical investigations revealed that event-specific training is equivalent for ET and CT two teams. This hints that the VR mode in that specific scenario is not harmful to training and seems to be as efficient as the typical learning method, but with higher upper and lower score, as well as smaller score deviation (more compact interval). In other words, the difference of distribution between both learning methods proposes that the VR learning offered a more consistent perception across trainees than conventional image-based learning (videos and slides), but more assessment would be needed to prove this.

The cause for the no significant difference in post-training scores of event-specific learning between the two teams may be that they are permitted to look into the essential learning materials once only, so there is not much difference in the familiarity of the two teams with the learning materials. To further explore the cause behind the results of section 4.2.1, a third team is also evaluated except evaluating the VR-based learning versus conventional image-based learning teams. Trainees watch the video (like CT), but there are no limitations on the use of the training video. Interestingly, before the post-training test, this team is discovered to frequently re-view video learning clips at critical sectors in time that involved solutions to the event-specific questionnaire utilized to assess training. Based on these situations, this team (M = 89.7, SD = 1.65) seems to have a higher learning effect than VR (M = 72.4, SD = 4.88). However, this manner has greater similarity between test answers for the trainees and greater diversity in response wording for trainees in the ET and CT who are permitted to watch the training contents only once. In the process of learning the same learning materials through two different learning modes, whether the number of repetitions of VR-based learning is less than the number of conventional image-based learning, there is a significant difference in their learning achievement grades compared to the grades of conventional mode, which has yet to be further verified.

Meanwhile, there are two factors of learning efficacy, learning experience and perception of existence, revealed to be noticeably better in ET over the CT. The indicated differences in learning experience between trainees from both teams propose that those in the ET, in spite of having obtained a similar quantity of learning contents, are sensation more certify the suitability of these contents. Hence, the results propose that the learning method with VR mode leads to a more involving mode enable trainees' confidence in their self-directed learning. Although the statistics show that the learning effects in terms of specific events is equivalent between the two teams, the ET participants are more engaged in terms of perception of learning. Because the VR education mode improves the participants' behavior and learning restrictions (space and time). Unlike conventional lecturing mode, in a settings executed by means of VR, learners can hope actual behavioral promotion because they are directly involved in specific activities, such as the appropriate operations to take in hazardous environment, including accidents that happen whether wearing protective equipment [55–57]. In this research, the chemical production safety learning platform is developed so that users can communicate with the virtual settings on the basis of VR techniques and realize the sequence of tasks, different from the existing traditional lecture approach. Besides, VR learning has a benefit of assisting training by enabling trainee to directly experience the topic of training while evading the hazard of incidents that may happen in an actual states under an unharmed settings.

Regarding effect of existence, it means the degree to which VR has a vivid sense of reality that not only maximizes the cognition, but also promote the trainee's response and vitality to enjoy the learning contents. On the basis of training contents that combines recent technologies, trainees are able to intuitionally communicate with the training topic being visually represented [58]. In this research, the immersive VR learning platform constructed to maximize learning engagement by offering experiential items that permit trainees to operate and communicate with training contents directly. This is of actual implication because it can naturally excite concern and involvement in chemical production safety training, even among participants with lower learning motivation.

In addition, availability of VR learning system is rated excellent in terms of the SoSA grade and impression analysis of response transcript. The proposed system is perceived as useful, easy to use, and satisfying to learn. This is consistent with the findings past researches [59–60]. As for the impression feedback, more positively emotional terms are mentioned in the ET. For example, 'like' the vivid VR environment, 'good' use experience in interactivity, 'easy' to deal with the specific event, very 'smooth' manipulation of the platform, etc. These feedbacks are, to some extent, consistent with previous studies [61–62], which summarized that experience of presence while applying haptic enabling technologies influence the perceived value of haptic enabling technology. Therefore, it could be summarized that the sense of existence during the VR-based safety learning has a substantial influence on the participant's faith about the learning, which plays a crucial character in promoting the efficacy of the learning.

Eventually, of the key indicators concerning the participant's task performance toward abnormal situations at the chemical production site, VR-based learning has a significant perception in usability. It is consistent with the finding of previous research [63]. This is a multi-indicator structure consisting of severity, damage level, and risk identification that has implications for perceived usability in health-related web application. Thus, infusing in learners a warning atmosphere related to unusual production situations could promote the entire efficacy of VR safety learning.

To summarize the above discussions, there are several issues implicated as below: (1) enhancing configuration of laboratory area – As a classification of region in a construction, chemical laboratories have more intensive facilities than offices or stowage regions [64]. The benefit to offer virtual learning of chemical safety could help for the combination and reclassification, more reducing utility and space expense damaging sustainability [65–68]. By generating the VR-based chemical lab platform, high expenses of utility related with working real chemical laboratory could possibly be obviously reduced; (2) connecting chemical engineering and cognitive behavior – By connecting calculated and mental evaluations of chemical safety learning, the presented experimental process could act as a scheme for later development in this novel multi-disciplinary study field. In truth, the demand to connect chemical engineering and mental technique clusters is emphasized in the past safety researches [69–70]; (3) meaning for chemical safety education – By asking trainees to finish vital topics virtually ahead of actual operation, the learning approach with VR mode has the possibilities to settle preservation of knowledge, learning turnaround time, topic of complex learning, and refinement of safety awareness. In the chemical engineering, researchers implement in a wide range, from labs to production factories. Thus, except beneficial safety simulations and learning activities, outcomes from this task are visualized to cultivate utilizations where remote virtual support can abate the eventual hazards to members on mass production sites.

Further study will also devote to probe the suitability and verification of the examination of perceived training experience applied in this analysis. Even though the experimental outcomes reveal the benefit of the VR learning approach for safety learning in chemical production environment, the sampling, especially the variability of digital literacy among trainees, may be an obstruction to this research. Hence, follow-up study should investigate the learning certainty of the presented method concerning a similarly digitally educated group of trainees to more strictly assess knowledge generation among experimental conditions.

6. Conclusion

Applying the specific events in UPR production process, an experimental workflow is introduced for the evaluations (learning efficacy and task performance) of an immersive VR-based learning against typical slide-based safety lecturing. It is conceivable that the identical workflow could be utilized to training generations beyond chemical production safety. There are several results shown in this study. Comparing the presented VR safety learning to DDChem developed learning modes, no significant difference is found for the learning effect of specific events in typical slide-based lecturing versus VR mode. Nevertheless, statistical differences supporting the virtual reality mode showed that trainees have positive sensations of confidence in learning, including participants find it useful for other complex tasks and helps to enhance decision-making. Most importantly, it allows participants to feel that it is possible to do their work independently. Furthermore, the trainees in the ET have positive investment in learning the content being taught. In addition, a more realistic and spatial perception for chemical production sites. Regarding the harmful sense, although trainees in the ET depict perceiving a less harmful senses than those in the CT, the result is not significant difference. Overall, the learning approach with VR mode has been revealed to assist trainees put more effort into safety training than conventional learning method. As for the proposed VR-based learning platform in this research, it is ranked as 81.64 by SoSA, marking it toward a grade excellent and well in the acceptance degree to provide qualified learning.

Meanwhile, the results of task performance offered through KPIs revealed that a learning approach on the basis of an immersive VR settings reconstructing the facilities of production factory helps the trainees, when compared to trainees learned through typical learning approaches, such as typical slide-based lecturing. Firstly, the trainees in the ET require fewer prompts than CT trainees during operation. Secondly, the average temperature deviation caused by the trainees of ET is smaller than that in the CT. Eventually, the trainees in the ET are higher achievement rate in recognizing the correct component as compare to those of CT. These results open the way for further research questions so as to amend the performance of trainees through advanced learning approaches in the production industry

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Appendix A

Questionnaires used to evaluate participant learning achievement

Questionnaire of learning achievement in chemical production safety

0. Personal information

(1) Age: ☐ Under 20 ☐ 20 – 22 ☐ Above 20
(2) Gender: ☐ Male ☐ Female

I. Questionnaires of learning efficacy:

1. Learning effect in specific events

Please try to describe your learning effect for the following specific events:

(1) What will happen if I do not wear PPE (Personal Protective Equipment)?
(2) What will happen if air is allowed to enter the reactor?
(3) What conditions can cause unexpected events during the reaction stage?
(4) What conditions can cause unexpected events during the dilution stage?
(5) What can happen during the tanking stage?

2. Learning experience

In your experience at your course during the training, about how much have you feel each of the following? Mark your answers in the boxes. Examples: ☑ or ■

(1) Recognized learning
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(2) Easeful of begin physical world learning
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(3) Comfortable performing the work independently
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(4) More lessons required before learning independently
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(5) Considered useful for other complex work
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(6) Considered useful to enhance decision
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

3. Perception of existence

In your experience at your course during the training, about how much have you feel each of the following? Mark your answers in the boxes. Examples: ☑ or ■

(1) Actuality
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(2) Perception of real space
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(3) Harmful sense
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(4) Involvement
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

4. Impression of participant feedback

Describe what you really felt in this course according to the following questions:

(1) How do you feel about chemical production safety after a typical learning approach? Please briefly explain

(2) How do you feel about chemical production safety after learning through the immersive VR approach? Please briefly explain

II. Task performance

This part is recorded by the interviewer according to the participant's handling of the accident at each stage of the VR platform.

(1) Trainee reaction time (Time between the occurrence of the accident and the time when the trainee starts processing, unit: sec)

(2) Temperature deviation (In the event of an accidental rise in the temperature of the instrument, the trainee is recorded as dealing with the temperature difference between the current temperature and the specified maximum temperature, unit: °C)

(3) Recognition of component (Can the trainee determine which component to control when an accident occurs?
☐Yes Name of component?___________________
☐No

(4) Number of prompts (How many times did the flashing light come on during each stage to avoid accidents, from the time the trainee started to handle the task to its completion?)

Appendix B

Questionnaire of usage of VR chemical production safety learning system

In your experience at your course during the training, about how much have you feel each of the following? Mark your answers in the boxes. Examples: ☑ or ■

I. Intuition

(1) Vividness of learning contents
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(2) The hand-held interactions with the VR mode are perceived as relatively intuitive
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(3) The HMD is discovered to offer pleasing enjoyment during the learning process
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

II. Satisfaction

(1) Perceived ease of use
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(2) Perceived the simulation is smooth and steady
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(3) Perceived it is in any way clarity
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

III. Efficacy

(1) You have acquired an adequate quantity of guides to help yourself all over their learning
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(2) Perceive the VR experience is moderate
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

(3) The VR learning is effective for staying safe at the chemical production environment
☐ being strongly disagree ☐ being disagree ☐ neutral ☐ being agree ☐ being strongly agree

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