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A Framework of Innovative Learning for Skill Development in Complex Operational Tasks

Abstract

As today's oil and gas projects are becoming larger and more complex, project managers are constantly faced with a number of concerns about schedules, budgets, productivity and safety. Operating an oil and gas facility is a process where workers refer to technical specifications to obtain the right information, identify the components, and then make a decision as to the adjustment or correctness. This entire process is iterative and triggers a learning process which may lead to improved proficiency as the cycle is repeated. The inability to find the right information or sequence within a cycle can contribute to efficiency losses. Jobsite training offered by qualified organisations and associations for the oil and gas industry is very limited, and the relevant training facilities and centres that have been established or considered in the construction agenda are far from sufficient to the growing standard of operators and industry expansion. This paper, underpinned by advanced innovative visualisation technologies, proposes a framework to improve efficiency and expedite the process of developing the complex procedural skills in operating and maintaining oil and gas facilities, through identifying scientific principles of enabling complex procedural learning approaches, developing proficiency-based learning approaches and corresponding learning curricula, and appraising learning outcomes according to developed skillset taxonomy. The proposed framework is tested under the development of an innovative and immersive Augmented Reality/Virtual Reality training system, which reveals significantly pragmatic benefits in terms of boosting up workforce productivity while bringing down rework. It is also demonstrated that embedding paradigms of transformative learning process while pedagogically adopting Information Communication Technologies (ICT) in curricula development and assessment regimes can help the sector significantly improve workforce safety.

Keywords:

1. Introduction

The rapid expansion of worldwide oil and gas industry has resulted in construction of a large number of Liquefied Natural Gas (LNG) projects since the last decade. This increase in LNG production has boosted the capacity of global liquefaction to 281 million tonnes per year at the year of 2012 and will expectably reach 366 million tonnes per year by 2017 (Corden 2012; JGC Corporation Annual Report 2012). Representing approximately 10% global capacity, the Australian LNG market has become the third largest LNG producing country in the world (Spedding 2015). Ongoing LNG projects, such as Gorgon, Wheatsone, Prelude, CSG-to-LNG and Ichthys, will see Australia's total production capacity increase from 24 million tonnes to 85 million tonnes per year by 2017; making Australia account for about 22% of the global share (Hardisty et al. 2012). Though a major stimulus for regional and national economies, wave of simultaneous construction and investment by oil and gas tycoons is not without a noteworthy challenge: an expected shortage of experienced and skilled labour (Hou et al.

2016; Hou et al. 2014a; Barbier 2013; Bahn and Cameron 2013). This has even become a very critical factor at the commonly seen schedule and cost overruns and casualty accidents (Kamalakannan and 2012). Within a couple of years, the current number of LNG training facilities will be far too few to handle the industry's increasing demands for skilled labour; further exacerbating the problem (Energy Skills Queensland 2012). On the other hand, as maintaining and operating complex LNG facilities is hazardous work, industry is highly concerned about workplace health and safety. Although the oil and gas industry enjoys an excellent reputation for workplace health and safety, there are often major consequences of committing even a small error during the construction or operational phases, as indicated by the accident statistics (Fabiano and Curro 2012; Burgherr et al. 2010). It is therefore incredibly important that employees are aware of safety protocols within a workplace and know how to achieve a safe and productive operational environment (Jawhar et al. 2008). However, it has been observed that industry has a very limited ability to analyse and understand the impact of different task settings with regards to productivity and safety issues (Skogdalena et al. 2011). For instance, the industry is still not confident to address how operation parameters can affect a worksite's productivity or how industry can effectively prevent maintenance accidents. One possible solution to improve workplace safety is to use industrial robots during potentially hazardous tasks (Nikolic 2013). The problem with this is that current automation and machinery cannot provide complete flexibility of a construction task that a human can; typifying complete automation of the construction industry unpractical (Feldmann and Junker 2003; Säfsten et al. 2007).

To gain hands-on skills and practical experience in a recognised qualification in such sector, traineeships should usually be task-oriented or entitled to both off and on the job options (Rafferty and Norton 2010). For instance, as safety experience is often acquired through on-the-job experience (Patterson and Shappell 2010), without jobsite training settings, some of the inherently dangerous factors cannot be readily identified. The efficacy of off-the-job approach is critically subject to a series of factors (Saks 2014), for instance: whether companies open sufficient training facilities; are those training facilities with restrictions on time and space allowance, investment, and expert knowledge. On-the-job training options though, are relevantly impractical, given that a real field scenario may be logically difficult and dangerous to be operated by a less well-trained worker, or unduly expensive to shut down a part of the site as part of a learning course. The fact, unfortunately, is that there is still a lack of established training facilities and effective training approaches across the industry. On the other hand, given the large and complex amount of assets to operate and maintain, the resources and efforts allocated to developing an advanced and organized training program could be significantly massive. In this sense, the industry-specific needs, for example, compliance with health, safety, environmental and operational standards, require a high level of understanding on what training metaphors are required for delivering effective learning outcomes. However, it is still ambiguous for the entire sector to justify what training metaphors can facilitate effective knowledge acquisition.

2. Literature Review

To foster efficient skill development through training, there are vast amounts of research work demonstrating very promising approaches (Bernold 2007; Dunston et al. 2011). Among these approaches, the mixed-reality technologies, such as Virtual Reality (VR) and Augmented Reality (AR), offer unique new viewpoints on the core goals of training and education (Wang et al. 2011; Hou and Wang 2013a; Wang et al. 2016). What distinguishes VR and AR from all preceding training technologies is the sense of immediacy and control created by immersion: the feeling of "being there" or presence that comes from a changing visual display dependent on individual's movements (Webel et al. 2011). A brief overview of existing mixed-reality research on training, skill transfer, education, and procedural and cognitive learning vastly demonstrates the promising facts of mixed-reality paradigms (Müller 2015): it can be means of enhancing, motivating and stimulating learners' understanding of certain events, especially those for which the traditional notion of instructional learning have proven inappropriate or difficult (Kirkley et al. 2005; Pan et al. 2006), it helps to develop a human's repertoire of physical actions and spatial abilities (Wang and Schnabel 2008); it affords a learning atmosphere under which concrete experience can be gained faster (Chen and Wang 2008); it significantly improves people perception about the geometrical features and spatial locations of components in operation task (Hou et al. 2013b); it facilitates a steep learning curve and enables effective rehearsal of future operations (Wulf et al. 2010).

Operation and maintenance of oil and gas facilities, however, is a more complex process which refers to an operational iteration to fulfil the function of equipment. In an oil and gas context, this process requires high-demanding manipulative skills, creative problem solving strategies, risk taking, decision-making, consciousness of occupational health and safety, and is normally conducted in dispersive positions in different climates (Patle et al. 2014). Although visualisation-supported learning has been shown to be an effective way to reduce cognitive load and enhance learning outcomes (Rapp and Gena 2014), the antecedent research has not bridged a critical research gap, which is how to apply such an approach to facilitate complex procedural skills learning, given the difference between complex procedural training and generic training. Prior research has vastly shown that VR and AR scenarios are effective for learning basic skills in the practice of construction, engineering and medical science (Huang et al. 2010; Nee and Ong 2013, Hansen et al. 2010), however, principles derived from simple skills training do not necessarily generalise to more complex skills such as identifying risk factors and troubleshooting complex faults. Therefore, the commitment to the utilization of mixed-reality technologies is still relatively infantile in complex procedural training and skill development realms such as oil and gas operation and maintenance.

Generic training that aims at teaching easily transferable skills values a realistic experience through simulating real-task scenarios (technological advancement of developing a training system) (Grossman and Salas 2011). However, in more complex procedural task training, devising appropriate curricula with underlying valuable human factor insights is so important because it underlines the fact that individuals perceive and interpret the same circumstances differently depending on their personal attributes and how they cognitively make sense of their surroundings. This comes up with another research gap: although studies have demonstrated the beneficial effects of novice training using VR and AR simulators, there is still no consensus regarding optimal training curricula and underpinned human factors for complex procedural training. In an oil and gas context, primary principles for productive and safe operation and maintenance are concerned about a variety of factors such as task proficiency, time consumption, error rate, motivation, mental workload and so on (Van and Printelon 2014). As these factors are of significant relevance to human behaviours, this project needs to derive a proficiency-based "mixed-reality scenario to real-world scenario" cognitive learning model. For example, when an operator is asked to behave someway, the investigator will apply "espoused theory" and "theories-in-use" (Naidoo 2002) to interpret the action he plans to do under certain circumstances and account for his subsequent actual behaviour. If inconsistency occurs, a number of contributors from human factor perspectives will be adduced, as the focal point of inquiry, to expound this inconsistency. To this end, a cognitive learning model that accounts for level of alertness, awareness of hazards and other distractions will be explored to develop proficiency-based learning approaches, where the amount of immersion which stretches from mixed-reality displays to a completely synthetic world (with haptic and sensory feedback) will mimic same factors of the real-world. The proposed training curricula will accordingly highlight the need to determine unsafe working conditions and acts associated to an activity, and identify areas where prevention efforts should be made for more effective accident prevention skill development. Therefore, this paper will establish and validate structured mixed-reality curricula to provide evidence-based learning approaches for improving efficiency, effectiveness, and safety through complex procedural training programmes.

Given enormous complexity of an oil and gas context, developing mixed-reality training programs and curricula requires comprehensive knowledge and understanding on oil and gas operation and maintenance and mapping of practical task settings to mixed-reality learning environments. Bring these two areas more closely together is another research gap that the proposed framework must address in order to effectively design and utilize these learning environments. A feasible approach is forming a collaborative design team (researchers, industrial practitioners and game developers) to synchronize the designing process of complex procedural tasks, task environments, human factor issues and pertinent mixed-reality systems. To illustrate, complex procedural skill development from mixed-reality environments leans heavily on trials and allow for risks and errors, therefore, the design team will structure learning environments that learners are offered the opportunity to engage with contents based on real world issues, to test learning outcomes, and to develop greater expertise through addressing complex procedural problems. Last but not least, there is also a need for the proposed framework to scientifically validate the learning outcomes in this relatively new research area. Without strong performance measures, the outcome in terms of knowledge learned and ability to transfer newly acquired skills to the real world practice is unknown.

3. Framework Development Outline

The ways in which the training communities define procedural skills of the targeted industry are fundamental to understanding how the learners form their learning mechanisms. In this regard, the framework proposed will investigate varied human factor and learning related theories, including procedural learning, visual-spatial skills development, and generic decision-making mechanisms. To this end, this paper aims to contribute towards the development of new learning approachesto significantly improve the productivity and safety of oil and gas workforce, which ultimately provide paradigms of transformative learning process of pedagogically adopting technologies in national curricula development and assessment regimes. Based on the abovementioned research gaps, the focus of this framework is therefore on what strengths will be well matched to the capability development of operators for complex procedural activities, and what training and learning settings are appropriate for a trainee to develop particular skills. Understanding these questions has great significance in training novice operators who are supposed to apprehend the knowledge of what and why to do (domain knowledge), how to decide what to do and when (strategic learning), and how to do (procedural knowledge) (Smith 2003). For instance, as the investigation of accidents normally occurs after the accidents, investigators often miss important clues and steps to help them understand the root causes of accidents. To facilitate the understanding of human errors that might potentially incur accidents, there is a need to look into viable technologies that help answer the questions of ‘‘what’’ and ‘‘how’’ during the investigation of contributing factors, without the accident actually occurring. It is also believed that by complementing these technologies with theories of human engineering and learning, developing technologies would result in a better understanding of the relation between the ‘‘antecedent human behaviour’’ and the accident at a level enabling the root causes of the accident. This expectation, however, is linked to a gap in construction management research of consistently failing to consider the crucial person–environment interactions in the study of project performance. A lack of exploration in these domains highlights such a research landscape: to further formulate a set of training and learning curricula, from which the skills of operation can be effectively formed and the root causes of productivity loss be identified for hazard prevention and efficiency improvement.

To this end, the framework proposes a novel proficiency-based cognitive learning model through mixed-reality scenario to real-world scenario cognitive learning, and a newmethodology underpinned by much of contemporary human cognitive research to examine learning outcomes. Such an attempt has hitherto received little attention, and therefore, is envisioned to generate scientific principles and guidelines for creating effective training systems and schemes in the development of transferable skill for oil and gas operators. Successful execution of this framework will also feature the innovative highlighting of shifting the traditional in-class or plant-based training to easier-to-deployed visualization precincts, with the possibility of both looking into some of the processes alike the on-site training and trying out different control settings and values, and ultimately leading to significant pedagogical insights within national curricula and assessment regimes. This framework is envisaged to:

1. Directly impact on the workforce productivity and economic growth: This framework will significantly improve the performance relevant to mistakes and reworking for the oil and gas sector, and allow the industry to address significant cost/schedule overrunissuesat a lower price, through implementing a series of hands-on training programs and curricula.
2. Upgrade workplace health and safety and social welfare: By delivering frontier visualizationlearning curricula and prototypes that contribute to expedited learning curve, the industry will be able to eliminate operator errors and accommodate a more diverse group of trainees to gain the necessary awareness of occupational health and safety.
3. Develop a theoretical foundation for a new class of technology-based learning: This framework will contribute to fundamental sciences by conducting original research into goal-directed behavioural decision making, and enable enhanced understanding, development, implementation, and assessment of a new class of technology-based learning approaches, particularly, for procedural learning in complex activities. The outcomes of this research can be readily applied to the architecture, engineering, and construction (AEC) industry in nationwide, and be promising to remedy the skill shortage challenges in a cost-effective and highly efficient way.

4. Methodology

4.1 Development of learning model and performance metrics in problem-solving and decision-making

This framework is to examine relevant human factor theories and develop a learning model that forms the basis of the study. A particular set of human factors were taken into account in addressing the scale of complexity inherent in oil and gas operation and maintenance, and these factors typically deal with a diverse range of human performance related to operational errors, productivity, and workplace health and safety. Human tend to make errors under circumstances where operation and maintenance tasks may occur in all weather and under time pressure, and task procedures might be implicitly written and facilities/tools might be difficult to access or simply not available. Nevertheless, humans are adaptable to environments, and could identify and self-correct errors before those disadvantages become irreversible consequences. To address those factors, the question becomes what are the human factor mechanisms in terms of problem-solving and decision-making that can enable human to avoid errors. This task used the PEAR (People, Environment, Actions and Resources) model as an instructive framework to identify human factors related to the tasks and conditions in the maintenance environment (Johnson and Maddox 2007). Pilot work has started in developing the learning model at the "*people tier*", and culminated in developing a skillset taxonomy that concerns physical, cognitive and other human factors (e.g., fatigue, stress and motivations).

There are numerous critical indicators that have been identified for evaluating people's performance in this tier. In order to work out a breakdown structure of the performance metric with measurable variables in the context of skills development of people, a wide range of skillsets in terms of trainees' propensity to apply what they have learned and the actual capabilities they have developed are illustrated. To foster domain-specific knowledge, the trainees need to master how to perform procedural tasks under a particular circumstance. The system could provide a representation of a series of tasks as hierarchical steps, each of which is either a primitive action (e.g., press a button) or a composite action (i.e., itself a task). Constrains in terms of activity ordering or available resources will also be specified among the steps, namely, one step must precede another or one resource will not be ready until an action is implemented. However, the performance of a specific task offers no indication regarding the capabilities that trainees could demonstrate when they are confronting another task that requires them to apply their acquired skills (domain-independent knowledge). This problem could be resolved by predicating upon the 5-stage skill acquisition models defined by Dreyfus et al. (2000), and by incorporating memory related learning paradigms (Hyman et al. 2006) with an assessment of trainees' performance in a new task setting that requires higher skillsets.

Table 1. Development of skillset taxonomy, underpinned theories and indicators

Underpinned human factor theories	Operation of Proficiency (K1)				
	Visual-spatial (P1)	**Psychomotor and Cognitive (P2)**	**Kinesthetic (P3)**	**Self-efficacy (P4)**	**Others (P5)**
spatial cognition; active vision; instructional design and learning; working memory; espoused and in-use theories	1. locate equip per crew or per shift 2. understand what to do 3. sensory exploration of the environment 4. work-piece alignment 5. continuous scanning for object searching 6. access to engineering information during inspection 7. collect data needed for maintenance 8. access certification documents 9. and others	1. coordinate activity involving the arms, hands, fingers, and feet 2. think about every detail 3. make conscious cognitive assertion 4. derive information about one's environment 5. understand workflow 6. evaluate, ensures the materials achieved the desired goals 7. encode and retain maintenance instruction as a short memory 8. refer to instruction 9. and others	actual actions such as lower, close, move, connect, press, disconnect, raise, hold, set join, align, track, regulate, transport and synchronise, etc.	1. approach goals, tasks, and challenges 2. level of confidence about capabilities to implement actions to attain designated performance successes and failures at achievement tasks 3. effort expenditure and persistence 4. anxiety symptoms 5. and others	1. level of communication 2. amount of wasted resources 3. take the initiative to correct mistakes
goals-freedom-alertness theory; adjustment-stress theory; distractions theory; accident root causes tracing model	**Operation of Safety Compliance (K2)**				
	1. level of alertness 2. consciousness of permit and awareness of hazards 3. visual distractions 4. and others	1. divert the attention of workers 2. propensity to cause fatigue, worry, anxiety 3. and others	1. low-quality work behaviour 2. propensity to physical strain, susceptibility to injury 3. and others	1. occurring in an unrewarding psychological climate 2. set attainable and well-defined goals 3. level of task achievement 4. and others	1. incompatible goals 2. organizational failures 3. poor procedure 4. error-enforcing propensity 5. and others
(N) Novice; (A) Advanced beginner; (C) Competent; (P) Proficient; (E) Expert *Novices may be able to describe the steps in which they engaged to perform specific task episodes better than experts can, due to the novices' greater reliance on attention and working memory for task performance, but the experts possess more detailed domain-independent knowledge of a generic nature about how the tasks are performed (Beilock and Carr 2001). Our concept of assessing learning effects is thus informed by a series of rating techniques including after-action review, level of locomotion, motor control, fatigue, gaze, attention-directing cues, etc.					

4.2. Development of a mix-reality training system, testing of learning scenarios tied directly to realistic scenario events, and establishment of pedagogical curricula

A video game development engine named Unity was used to develop a mix-reality training system. This engine was chosen because it is cross-platform compatible and expandable, and easy to customise and operate scenarios. It supports scenario customisation via user scripting in various language such as JavaScript, C# or JS (users are allowed to retrieve different scripts that are open-sourced and formulate their own scripts). At present, this system has been tentative prototyped and functioned to generate varied task-specific AR and VR scenarios. More technical details are provided in the next session. To foster domain-specific knowledge, the trainees need to learn how to perform procedural tasks under particular curricula. Within these curricula, the research inspectors can make explicit statement about learning effects. To this end, the proposed curricula incorporated activities from which a learner's knowledge or skills can possibly be constructed and acknowledged based on the performance index developed from Task 1. A number of pedagogical methodologies of establishing curricula were then reviewed from which the pertinent were be applied, for instance: applying "constructivist learning" to continuously examine learners' performance; applying 'in-situ simulation" and "context-aware ubiquitous learning" to examine what skills learners may cultivate; and implementing "reflexive learning" to assess individual experiences and other variability. Next, to rate appropriate level of task proficiency and skills learned (assessing the amount of a series of intentional responses that gradually lead to a success/failure of the task), the study casted the focus onto a few primary, yet assessable indicators centred on the human behavioural perspective, i.e., visual-spatial; psychomotor and cognitive; kinaesthetic; self-efficacy and level of resources. It might be appropriate, for example, to award a learner a 'Proficient' badge because he could meet the required level of kinaesthetic competence, despite the fact of lacking prior 'hands-on' experience (assuming 'hands-on' is an imperative element of 'Proficient'). This situation could be tackled by stipulating in the curricula that the learner should start the primitive tasks on relatively simple settings in the first place. Furthermore, the transition in degree of difficulty was assured to be relatively effortless to all the subjects, which was imperative to form an optimal learning process.

4.3. Implementation of training curricula and longitudinal experimentation to validate learning effects

The framework will also validate the hypothetical development that concerns the effectiveness of the visual platforms for different learning styles, the characteristic of skills to be learned, and proficiency levels. The learner in this task will demonstrate knowledge acquired from curricula based training by solving authentic problems. The experimental design consists of three distinct phases: assessment of learners' background, main experiments and evaluation. First of all, a pool of trainees will be assembled. The immediate design is to have a number of learners of each proficiency level (novice, advanced beginner, competent, proficient and expert). After their background is assessed, using questionnaire such as the Learning Type Measure (LTM), the learners from each proficiency level will randomly be assigned to one of the mixed-reality training scenarios. Secondly, following a standard instruction, the trainees will be introduced to the mixed-reality system and allowed to familiarize themselves hands-on with pre-training session. The experiments will be following developed curricula developed in 4.2. For pedagogical reasons, the training at each level will be organised in sessions with sufficient time between sessions for the learners to process what has been learned. Such phased training can result in an increased skill retaining over a longer period of time, and allow faster learners to move quickly from one session to the next (slower learners may repeat a session before moving to the next). To encourage continuous skill transferability, one more step immediately following experimental measurements is to identify whether the skills acquired from virtual workplace environments will occur accordingly in real environments. In this sense, a user-centred summary assessment, an educational methodology to validate external accountability from controlled environments, will be conducted to collect authentic feedback.

5. Pilot Experiments and Results Analysis in a LNG Maintenance Case

5.1. Site layout, instrumentation and training scenario setup

The oil and gas site is located at the Australian Centre for Energy and Process Training (ACEPT) operated by Challenger Institute of Technology in Australia. It is a process operations provider which offers certified training qualifications for the Australian oil and gas, mineral and chemical processing industries. The researchers were granted access to the facility. The designated training area includes a schoolrooms area and a training field area. The training field was about 1,734m^2 large (Figure 1). The pilot experiments were particularly focused on removal of a pump on the dehydrator of the field. The training session required a number of components of different functions and specifications to be dismantled, maintained and reinstalled.

Figure 1. Layout of the pilot experiments in the ACEPT site

The traditional training paradigm was accessing, interpreting and applying work sheets and instructions, for instance, P&IDs and risk assessment sheets, to perform the allocated operation and maintenance tasks. AP&ID (piping and instrumentation diagram/drawing) is a reference diagram which shows the piping of the process flow together with the installed equipment and instrumentation (Figure 2). The to-be-maintained component, a pump in this case, is located in the pipe session as circled. Figure 3a states an overview of the physical pumps and pipelines of the dehydration unit, of which the pertinent isometric drawings are stated in Figure 4. To maintain a pump without shutting down the entire facility as stated in Figure 5, for example, it is necessary to close the pipe of which the pump is attached and then open another pipe for the liquefied gas to bypass. By shutting two ball valves (12 and 13), a section of the pipe can be closed up and then the pump P-141 can be securely removed. Traditionally, the maintenance work follows a six-step workflow as stated below:

1. Identify critical pipes and devices to be temporarily bypassed
2. Mark devices to be bypassed in P&ID
3. Perform safety induction
4. Perform and monitor bypasses/ blocked-out functions
5. Complete start-up, shutdown, operation, maintenance, or testing activities
6. Check/verify work completion and notify site personnel before removing the bypasses

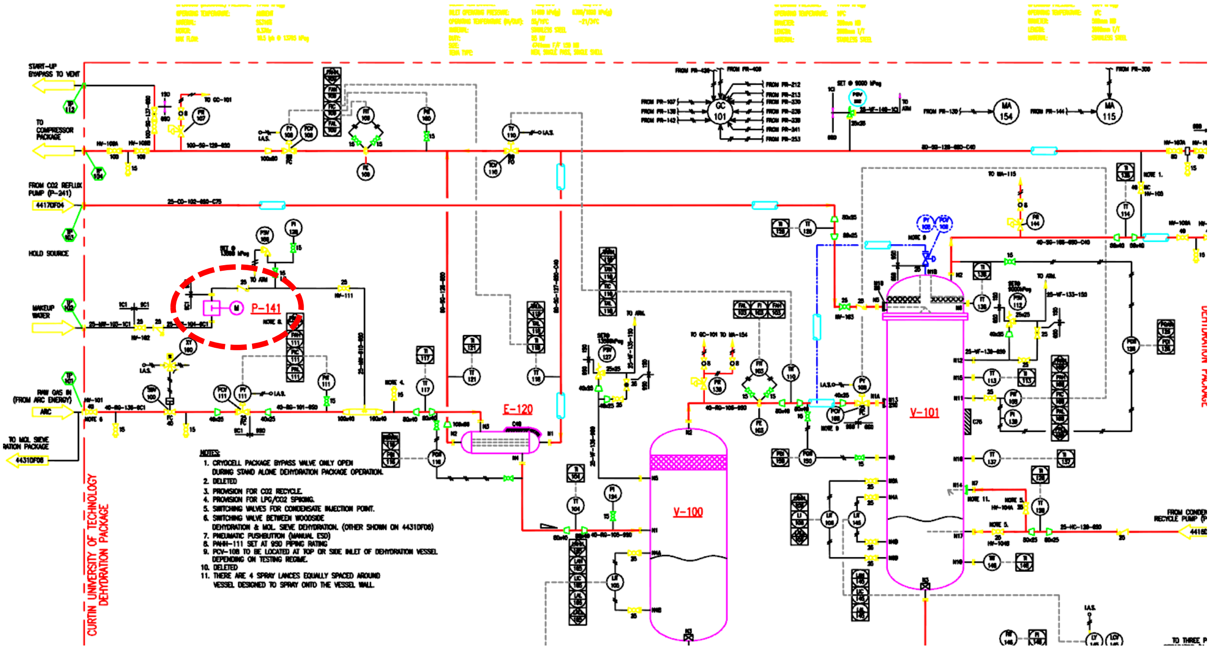


Figure 2. A P&ID drawing of the dehydrator and the to-be-maintained pump

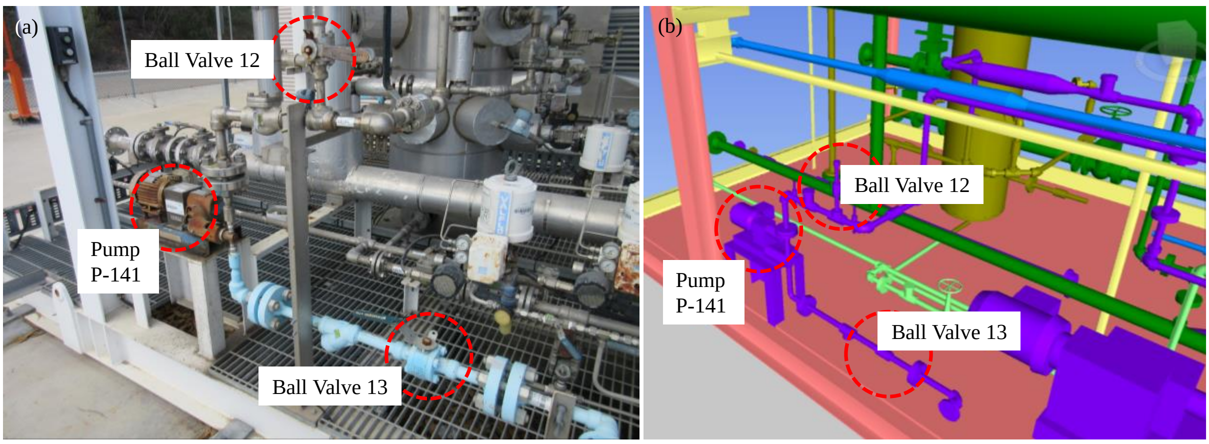


Figure 3. The overview of the pump P-141 and related pipe system: (a) Field instances and (b) associated models in the virtual environment

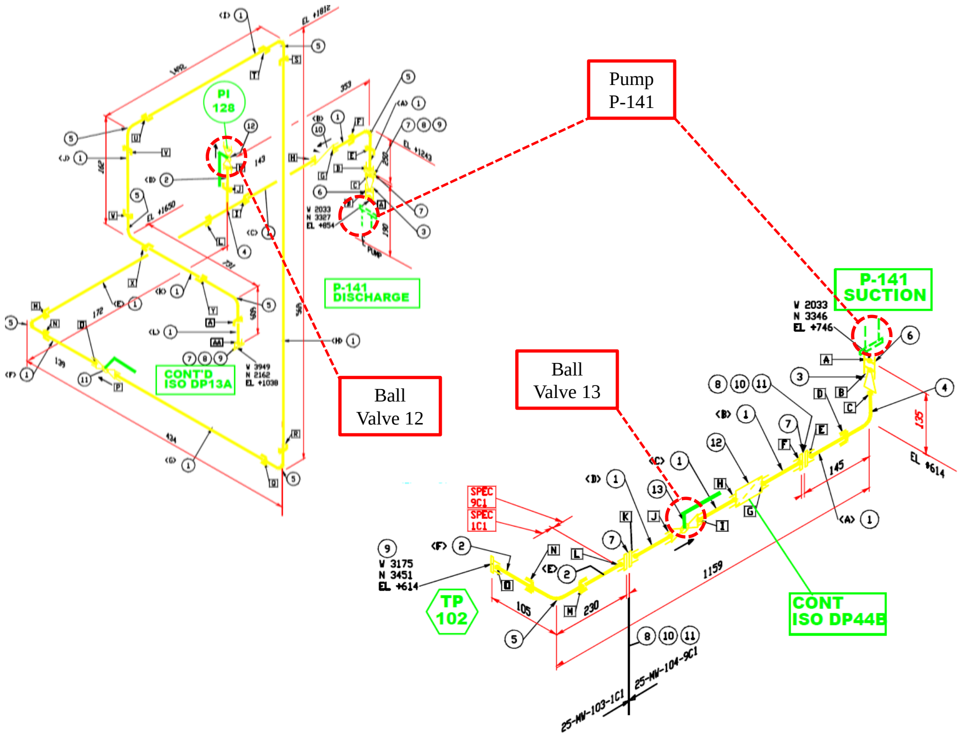


Figure 4. An isometric view of the pump and related pipe system

Figure 5. Simulated pump P-141 blocked-out and removal training procedure: (a) switch off the ball valve 13 and (b) 12; (c) unbolt connections of the pump and related flanges, and (d) the pump removal

A material lay down yard was allocated near the workshop and around the dehydrator to temporarily deposit the components and tools. With the deployment of four video recording cameras, the researchers were able to observe and collect the intra-training and post-training activities of 10 trainees. The goal of the experiment was to analyse and compare the safety and productivity performance data under two ways of training paradigms. Our pilot work has started with developing a sample curriculum (Figure 6) for the skill level of *Competent in Operation in terms of Safety Compliance (K2)*, followed by a pertinent, yet conventional paper-based training manual to instruct trainees to solve the problems step-by-step, to use the right tools, and to understand the workspace-related factors (Figure 7). As against this approach, an innovative AR/VR training scenario is demonstrated. With this platform, trainees can virtually interact with a scenario tailored for specific task requirements and rehearse the task procedures as afore-listed (Figure 8).

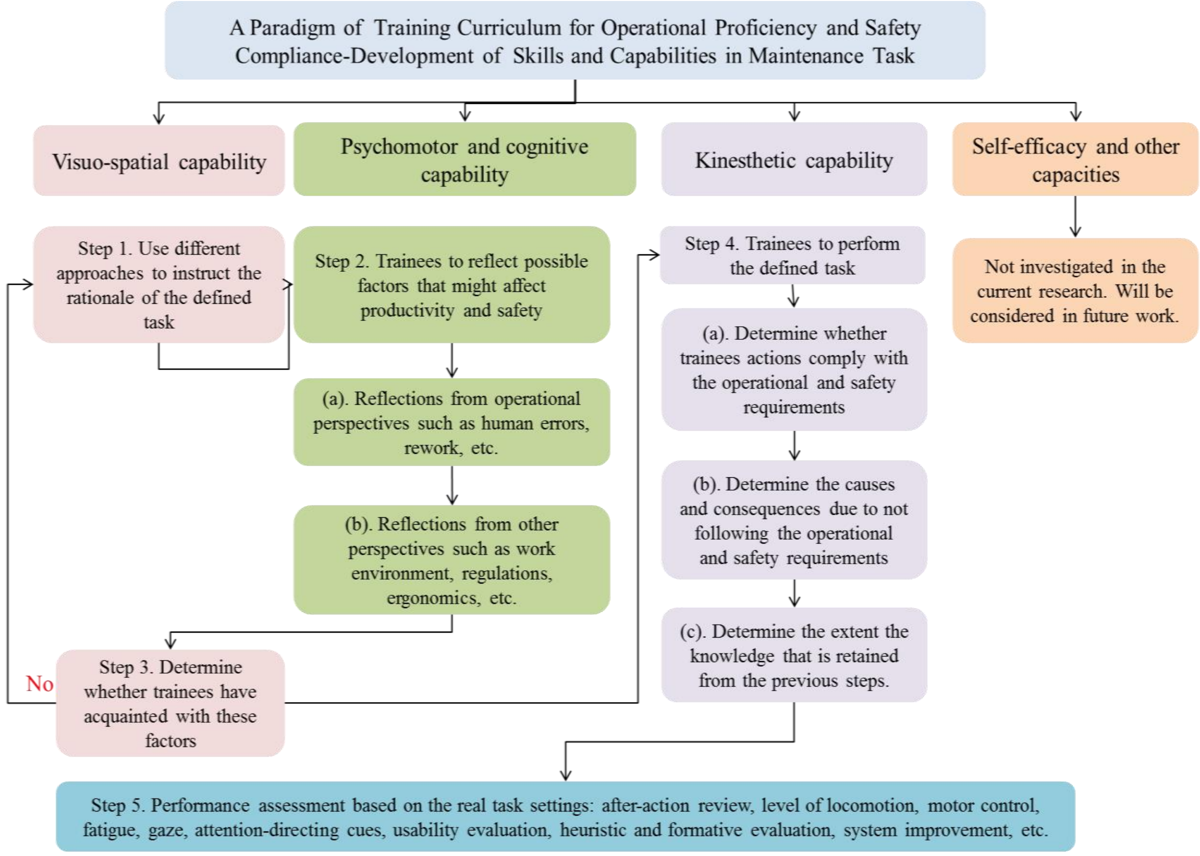
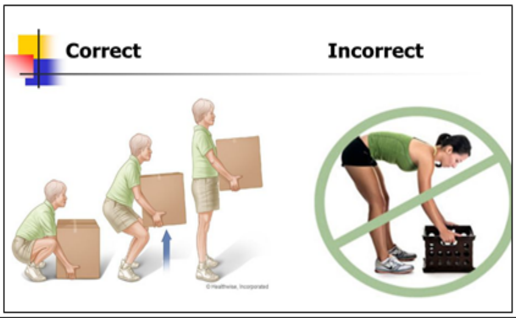


Figure 6. Curriculum exemplar for the skill level at K2

<table>
<tr><th>Step</th><th>Work Item</th><th>Content of Work</th></tr>
<tr><td>1</td><td>Work Permit Acquisition</td><td>Check work permit & understand job requirements</td></tr>
<tr><td>2</td><td>Gas Leak Detection</td><td>Use gas detector to check if there is gas leak around the dehydrator</td></tr>
<tr><td>3.1</td><td>Pipeline Isolation</td><td>1. Switch off Ball Valve 13 (See attached drawing ISO DP44A)
2. Switch off Ball Valve 12 (See attached drawing ISO DP45)</td></tr>
<tr><td>3.2</td><td>Preliminary Safety Precautions</td><td>1. Ensure pumps are cooled down to room temperature before commencement
2. Heat insulated pads need to be set in place prior to pumps removal</td></tr>
<tr><td>4.1</td><td>Safety Precautions</td><td>1. Beware that pipelines may have LNG residual
2. Ensure all openings are fully sealed
3. Apply the correct posture when carrying (see photos)


Experimenter ID.</td></tr>
<tr><td>4.2</td><td>Dismantling</td><td>Disassemble the pipelines by using wrench Order:
1. [ISO DP44A] A, B, C, D, E
2. P-141
3. [ISO DP 45] F</td></tr>
<tr><td>5</td><td>Signing off</td><td>Please remove all tools, equipment, personal locks and sign off work permit</td></tr>
</table>

Figure 7. Exemplar of paper-based training manual

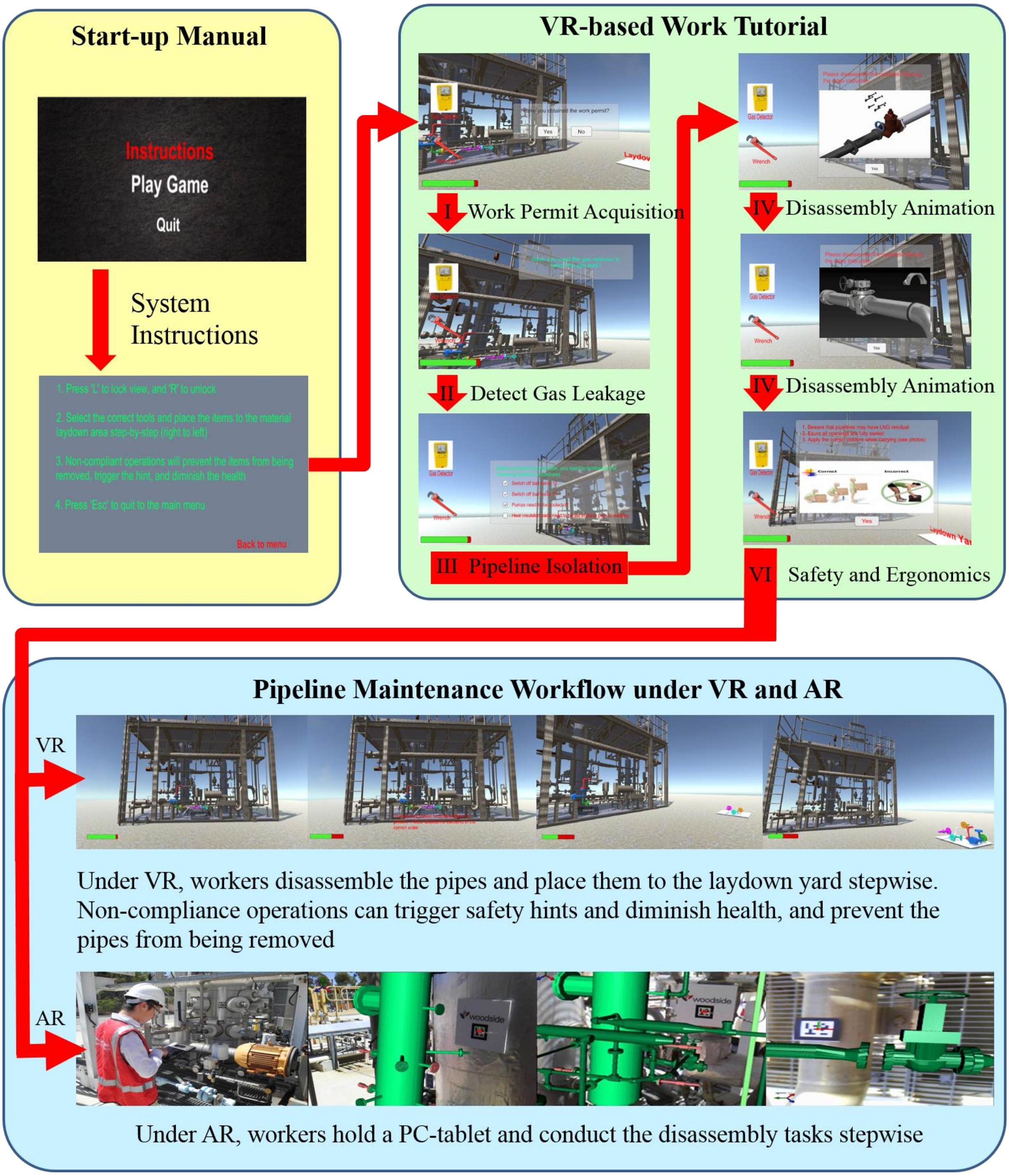


Figure 8. AR/VR mix-reality training system for procedural maintenance tasks

5.2. Experiment evaluation for productivity and safety enhancement

The experiment process is designed to investigate into whether productivity and safety difference could be manifested across two training approaches. It consists of two phases, namely, cross-over comparative experiment and post-experiment usability evaluation. The objective of the cross-over experiment is to study the nature of cognition on a person's performance when merging digital virtual information (e.g., AR/VR clues) opposed to physical information (e.g., paper contents) in a real LNG pipeline maintenance workspace. The criteria of performance evaluation were set forth in accordance with the universal interpretation of productivity derived from manufacturing.

With Eq. 1, first of all, productivity is referred to as a ratio of quantity of installation/uninstallation against task duration:

$$P = \frac{W}{Mh} \tag{1}$$

where P denotes productivity; W represents weight of completion; M is the number of workers and h refers to the duration of the task.

Second, productivity also represents the accuracy of leading to the as-planned outcomes, which is reflected from the following two perspectives:

$$P = \frac{1}{C} \tag{2}$$

$$C = \sum_{i=1}^{n} w_i C_i \tag{3}$$

where C denotes the derived cost related to the performance of the participants, which is the sum of weighted (w_i) costs (C_i) under the consideration of efficiency, effectiveness and safety (Table 2). It is noticed that the derived metrics did not include an effort to set forth the components, acquire the work permit and prepare the inspection in that these activities remained insignificant of the way the task was conducted. Last but not least, a usability questionnaire was developed and marks were collated in order to assess the participatory process and certain features within the AR/VR space and the conventional paper-based manual (Table 3).

The two-group crossover design, also known as the standard crossover, was originally planned in the experiment (Hou et al. 2013c). The main justification for adopting this design was to minimise the effects of the learning curve imposed by the different sequence in presenting the two treatments. This is true in this experiment where the two treatments were contrasted. The sample size was decided on the basis of Cohen's d benchmark (Franke et al. 2010). This is the appropriate measure to use in the context of a t-test on means. In this experiment, the value of Cohen's d for the 95% confidence interval was tested on a scale of small to medium size effect of crossover design, indicating that a minimum of 10 participants (20 datasets) was significant enough for the purposes of the outcomes of the research.

Table 2. Productivity and safety metrics

Category	Metrics	Description	Formulae	Annotation
Efficiency	1. Man-hours	Totalled up time upon task completion by adding up the time of each milestone. It is the typical factor for labour productivity measurement.	$C_{mh} = n_h \times h$	n_h: number of participants h: man-hours
	2. Travel distance	Totalled up walking distance upon task completion. It could be linked to ergonomic analysis.	$C_{td} = D$	D: walking distance
	3. Rework	Totalled up time to rectify operation errors such as messing up steps, using incorrect tools due to understanding, negligence, etc.	$C_{ec} = \sum_{i=1}^{n} Te_i$	Te_i: time to rectify the i^{th} step
	4. Learning performance	Totalled up time to comprehend task requirements and implementation procedures.	$C_{lp} = T_l$	T_l: time to comprehend the i^{th} step
Effectiveness	5. Number of errors	Totalled up operational errors. It could reflect the quality of training.	$C_{et} = n_e$	n_e: numbers of errors
	6. Milestone performance	Totalled up times of succeeding or failing to complete specific milestones of the task.	$C_{mp} = \sum_{i=0}^{n} m_i$; $m_i = \begin{cases} 0, & success \\ 1, & failure \end{cases}$	m_i: result of the i^{th} milestone
Safety	7. Working posture	Observed/reported occurrence of awkward postures, i.e. bend-overs, lifting and carrying weight, etc. It could be captured using a real-time surveillance camera and used for ergonomic analysis.	$C_{wp} = n_u$	n_u: number of awkward postures
	8. Regulation compliance	Awareness of safety. A worker needs to conform to safety regulations and rules such as minding gaps between pipes, checking gas leak, wearing PPE, avoiding step on pipes, etc.	$C_{rp} = n_r$	n_r: number of not conducting safety check
	9. Use of tools	Awareness of using correct tools such as wrench, plier, screw driver, etc.	$C_{ut} = n_t$	n_t: number of using incorrect tools

Table 3. Questionnaire-based usability analysis (round-off means)

Post-experiment usability survey: AR/VR vs. Paper-based		
This survey invites you to respond to the questions from the next page. Your response will help the research team to conduct the usability analysis, understand the issues and improve the different training approaches. In order to ensure the credibility of your feedback, please feel free to ask the researchers for clarification. When you finish your survey, please double check your answers and make sure they are the most appropriate ones. Please characterise your experience in the different metrics, by ticking the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels.		
Scale: (1) Strongly Disagree; (4) Borderline; (7) Strongly Agree	AR/VR	Paper-based
1. Overall the operation under this approach was easy.	7	5
2. I could easily and quickly learn how to operate under this approach.	7	7
3. I could effectively complete the designated training task.	7	5
4. I felt comfortable when I used it.	6	6
5. When I encountered an issue I could quickly figure out the solution.	7	6
6. The training clues (safety instruction, operation rule and warning) were clear and explicit.	7	7
7. I could locate the right and relevant information.	7	5
8. The contents were easy to understand.	7	4
9. The training approach was nice and amicable.	6	6
10. The training approach had all expected functions and was feasible in reality.	7	6
11. Overall I was satisfied with the training.	7	5
Avg.	7	6
Open-ended Questions		
1. In general, how did you feel about this task? Easy? Or too hard to perform?	Easy	Intermediate
2. How did you feel about the use of the training approach?	Clicking buttons on the screen was not sensitive.	Not easy to find a component on the model based on the provided manual.
3. Do you think the training contents design is rational?	Yes. It helped me find out the target of interest and similar to what I	Yes. I think they do use drawings to identify the place of

	could see during the task execution.	maintenance target.
4. Is there anything you could suggest to help us improve?	Lay down yard needs to be enlarged. Need more instructions between each steps of the simulation.	The annotations on the drawing should be clear for recognition.
5. How did you feel about the flow of this experiment?	I have no problems at all.	Good

5.3 Data analysis

In the cross-over experiment, the experimental group used the digital virtual information (AR/VR clues) while the control group used the physical information (paper contents) for training the participants to study the nature of cognition on a person's performance in a real LNG pipeline maintenance workspace. In the category of efficiency, the man-hours (sec.), travel distance (m), rework time (sec.), and learning performance (sec.) to complete the task were measured and analysed using t-test for the two groups of participants. In the category of effectiveness, the total and average numbers of operational errors and failures to complete the task were calculated. In the category of safety, the total and average numbers of awkward working postures, violating safety regulations and using incorrect tools were calculated.

The statistical results of t-test on the man-hours spent by the control group and the experimental group to complete the task are shown in Table 4, indicating a significant difference exists between the two groups ($p<0.05$). The average man-hours spent by the control group (1022.8) is significantly larger than that of the experimental group (497.2). In other words, using the AR/VR clues for training the workers can save the man power to complete the task and thus increase the productivity.

Table 4. Statistical results on man-hours spent to complete the task

Group	Average	Standard deviation	t	Significance (p)
Control group	1022.8	430.0	3.045	0.007
Experimental group	497.2	334.9		

The statistical results of t-test on the travel distances made by the control group and the experimental group to complete the task are shown in Table 5, indicating a significant difference exists between the two groups ($p<0.05$). The average travel distance made by the control group (47.4) is significantly longer than that of the experimental group (37.2). In other words, using the AR/VR clues for training participants can reduce the travel distance during the task and thus increase the productivity. As against, more effort in searching required parts was observed in the control group, leading to a longer average travel distance.

Table 5. Statistical results on travel distance to complete the task

Group	Average	Standard deviation	t	Significance (p)
Control group	47.4	8.6	3.222	0.006
Experimental group	37.2	5.1		

The statistical results of t-test on the rework time spent by the control group and the experimental group to complete the task are shown in Table 6, showing no significant difference between the two groups ($p>0.05$). Although the average rework time spent by the control group (78.8) is higher than that of the experimental group (48.7), the data from the individual participants reveal that most of them spent about the same time on rectifying operation errors except that two participants in the control group required much longer time to fix the problems. Therefore, it can be inferred that both the paper contents and the AR/VR clues provided the participants with about the same training information to correct operation errors. However, the AR/VR clues were more capable of preventing some errors requiring a longer rework time and thus increasing the efficiency.

Table 6. Statistical results on rework time to complete the task

Group	Average	Standard deviation	t	Significance (p)
Control group	78.8	99.9	0.828	0.418
Experimental group	48.7	56.6		

The statistical results of t-test on the learning performance (in terms of the time spent to comprehend task requirements and implementation procedures) by the control group and the experimental group are shown in Table 7, indicating a significant difference exists between the two groups ($p<0.05$). The average learning time spent by the control group (1116.2) is significantly larger than that of the experimental group (728.2). In other words, using the AR/VR clues for training the participants can reduce the learning time and thus increase the learning performance.

Table 7. Statistical results on the learning performance

Group	Average	Standard deviation	t	Significance (p)
Control group	1116.2	403.6	2.117	0.048
Experimental group	728.2	415.8		

The results of effectiveness analysis (Table 8) show that the average numbers of operational errors (1.2) and failures to complete specific milestones of the task (1.1) for the control group are larger than those (0.7 and 0.5) of the experimental group, indicating the AR/VR clues can enhance the quality of training to avoid errors and failures during the task.

Table 8. Statistics results on operational errors and milestone failures

Effectiveness	Control group		Experimental group	
	Total	Average	Total	Average
Operational errors	12	1.2	7	0.7
Milestone failures	11	1.1	5	0.5

The results of safety analysis (Table 9) show that the average numbers of awkward working postures (1.4) and not conducting safety check (0) during the task for the control group are about the same as those (1.2 and 0) of the experimental group, indicating the paper contents and the AR/VR clues were both useful in providing safety training for the participants to avoid the awkward working postures and violating safety regulations. However, the average numbers of using wrong tools (2.9) during the task for the experimental group is larger than that (1.4) of the control group. It is inferred that the AR/VR clues are immersive and more interactive and therefore they may distract the attention of participants and cause them to use the wrong tools during the tasks. It is suggested that the AR/VR clues containing the parts for reminding workers to select correct tools such as wrench, plier and screw driver to perform a task are added to reduce the chance using wrong tools.

Table 9. Statistics results on working postures, safety regulations and using tools

Safety	Control group		Experimental group	
	Total	Average	Total	Average
Awkward working postures	14	1.4	12	1.2

Violating safety regulations	0	0	0	0
Using wrong tools	14	1.4	29	2.9

6. Summary, Conclusion and Future Work

Productivity, safety, and quality of the operation are inseparably tied up with the psychomotor skill of the workforce. However, conventional workforce education and upskilling do not take much advantage of applying emerging technologies to boost safety performance and required workmanship that can vary from one task condition to another. This paper starts with reviewing concepts presently used for upskilling and measuring skill levels in the oil and gas fields before it addresses the relationships between training and skill development. The main portion of the paper focuses on developing a framework to improve efficiency and expedite the process of developing the complex procedural skills, predicating upon the pedagogical settings. The framework is further tested under the development of an innovative and immersive AR/VR training system. According to the experimental results, the AR/VR training system can save the manpower and decrease the travel distance during the work to increase the efficiency. It can also reduce the learning time to improve the learning performance. Considering the effectiveness and safety issues, the AR/VR training system can enhance the quality of training to avoid errors and failures during the task. The outcomes of this study could help the AEC industry to significantly improve the productivity and safety of its workforce, while providing paradigms of transformative learning process of pedagogically adopting ICT in curricula and assessment regimes. Significant scientific and technological principles derived from the framework development could lead to new knowledge on complex procedural proficiency-based training, providing a focal point around which a critical integration of ICT and human factors research can be assembled and synergised.

It is acknowledged a current limitation that data from real working environments cannot be synchronised into the mixed-reality system in real-time might inhibit the utter effect of solving many of the causes that relate to visibility-related accidents. With further support of real-time sensing technology, such as motion detectors for ergonomic risk analysis, active RFID or UWB for component identification will contribute to the establishment of content-awareness learning environment, helping the detection of uncertainties in operations. In addition, robust wearable and haptic devices, like AR/VR headsets (Google glasses, Oculus Rift, Hololens and so forth), can also help provide just-in-time, information-rich and ubiquitous guidance for trainees to foster safety perception abilities. It is critical that such integration is enabled and validated in the future.

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