Impact of training methods on Distributed Situation Awareness of industrial operators

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Received 14 February 2014
Received in revised form 19 October 2014
Accepted 20 November 2014
Available online 11 December 2014

1. Introduction

In 2011, 539 billion euros worth of revenues were generated from the chemical industry in the European Union alone with the total number of employees being about 1.1 million (CEFIC, 2012). Chemical processes are inherently risk prone. The risk is monotonically increased due to the concentration increment of industries with hazardous productions and higher population densities around exposed areas. An industrial accident can result in the disruption of workflow, equipment damage, operator injury, and may result in several fatalities/casualties. Stark reminders of these risks can be found in a number of accidents, such as the Union Carbide in Bhopal (1984), AZF in Toulouse (2001), BP refinery in Texas City (2005) and the BP Deepwater Horizon rig in Gulf of Mexico (2010). An accident may produce severe consequences for the environment and civil population surrounding the plant (e.g., AZF in France, 2001). The involved companies may also face major economic repercussions (e.g., BP fine after Deepwater Horizon accident) that result in major economic consequences in addition to loss of production and reputation. Measures have been taken to reduce accidents. However, the number of industrial accidents per year is still growing (Pariyani and Seider, 2010) and the possibilities of accidents in the chemical industry are a major societal risk factor. A number of literature reviews have pointed to the main source of accidents as being the incorrect manipulation of process units by the operator(s) (Coleman, 1994; Antonovsky et al., 2013). Kletz (1998) mentioned that accidents occur and re-occur in the process industry because of the inefficient use of infor-mation and the lack of learning from the lessons that are available from accident data. As a measure to mitigate the limitations of human capacity, and thus to reduce accidents, automation has been introduced (Woods et al., 2010). Automation, however, brings with it a number of challenges of its own as outlined below.

1.1. Automation in industrial processes

The increase in the complexity of modern process control systems (Hollnagel, 2008; Nazir et al., 2014) which begun with the inclusion of automation-related tools and technologies, has significantly altered the work of process industry operators (Hollnagel, 2001; Norman, 1990. See Dekker and Woods, 1999, for specific examples). Specifically, before the automation era, industrial operators manually intervened in the controlled process.

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Consequently, industrial operators were needed to (physically) gather information about the process and make process adjustments (Emigholz, 1996). As automated process-control systems were implemented, the work of industrial operators was revolutionized from direct manipulation and control to supervisory activities involving the supervision from centralized control rooms (Hollnagel, 2001). For a single operator, some of the complexity lies in the diagnosis of fault situations that require a different approach to problem solving, i.e. an analytic approach that is not needed during normal operations (Patrick and Morgan, 2010).

In complex systems such as chemical process plants, work tasks are distributed among different elements/agents (both human and machine) and correct communication can be vital for the safety of process (Sessa et al., 1999). The operators can be at different sites (physically distant) whilst performing tasks that need coordination to ensure a safe and continuous production. Sessa et al. (1999) and Patrick and Morgan (2010) emphasized that the nature of information, distinguished by being distributed over the whole system and part of continuous collaborative efforts among different agents, can guarantee safe operations. This argument reflects the importance of teamwork and reliable communication among the members of team(s) in the case of industrial processes.

1.2. Teamwork and communication

Teamwork is defined by Wilson et al. (2007) as "a multidimensional, dynamic construct that refers to a set of interrelated cognitions, behaviors and attitudes that occur as team members perform a task that results in a coordinated and synchronized collective action" (p. 5). In the case of process industries, operators are divided into two broad categories i.e. Field Operators (FOPs) and Control Room Operators (CROPs). Typically, FOPs interact with physical devices that are distributed throughout the plant and can thus use some of their senses, i.e. sight, sound, and touch (only occasionally smell and very rarely taste) to crosscheck the perception that is formed by the interpretation of field data from sensors. Conversely, CROPs are typically involved in observing an artificial representation of the real environment, where a number of synoptic displays of the Distributed Control System report the key process variables, which are often complementary to those that are experienced by FOPs (see Fig. 1a and b). In addition, under normal operations, there is periodic communication between FOPs and CROPs to assure continuous and safe operations.

Although both FOPs and CROPs are focused on the same process and equipment, they have different bases for perceiving the environment, understanding the importance of the information (e.g., creating meaning out of the information), and interpreting the incoming information. Process industry is a good example of a complex socio-technical system, where the elements of the systems are geographically distributed, and shared between FOPs, CROPs, and the artifacts with which they interact. During normal operating conditions, FOPs and CROPs communicate on a number of occasions to verify and understand the system status (e.g., operating conditions). As the operating conditions deviate from the optimal range, uncertainties are introduced into the system and normal operating procedures are no longer sufficient to assure the process' safety (Wickens and Hollands, 2000). A different level of problem solving is required by FOPs and CROPs to assess the situation (which falls beyond the normal conditions) and establish a course of actions to eliminate the uncertainties and return the system to normal operating procedures. FOPs, by virtue of being in the field, have direct access to the equipment and can consider the information displayed directly on measuring devices. The CROPs, on the other hand, have access to status information of larger sections of the plant and so use the detailed information from the field to integrate with their wider understanding of the status quo of the system. Under both normal and abnormal opera-tions, FOPs request information from CROPs to gain an extended understanding of the status of the plant section where they are operating, with the aim to enhance their process understanding that comes from the direct (but incomplete) experience of in-the-field instruments and equipment. CROPs, on the other hand, require information from the FOPs to understand what is going on outside of the control room to contextualize the displayed infor-mation and add details to the remotely acquired measures. This two-way information sharing is vital to control the processes and preserve the plant safety. Consequently, FOPs and CROPs commu-nicate and coordinate on a continuous basis to weigh and analyze various elements of the situation in order to reach a decision. Therefore, the successful interaction between CROPs and FOPs, enables the responses which can avoid an accident. Unsuccessful interaction, on the other hand, makes the system less safe.

As shown in Table 1, FOPs and CROPs have different information bases on which to form their understanding and subsequent decisions.

Thus, the CROPs' and FOPs' awareness of the process status is based upon substantially different stimuli. The tasks performed by CROPs and FOPs are also not identical in terms of attention requirement, mental workload, responsiveness, and decision-making capability. Furthermore, the information that reaches CROPs and FOPs varies in terms of their nature and sources.

This significant difference in inputs and tasks of operators can trigger misunderstandings and communication errors, which may lead to unsafe and hazardous conditions (Nazir et al., 2012). The accomplishment of a task by a team composed of CROPs and FOPs requires distributed knowledge, collective dynamic understanding, and shared mental modeling (Orasanu, 1990). The task may also be so large and complex that work is shared among individual team members (i.e. a main task is split into sub-tasks). For instance, teams of operators are needed to complete some difficult procedures, such as start-ups and shut-downs, because a single operator or even a couple of operators, e.g., a FOP and a CROP,

(a) A typical CROP activity

(b) A typical FOP activity

Fig. 1. (a) A typical CROP activity. (b) A typical FOP activity.

Table 1
Input information and selective task for FOPs and CROPs.

Input information	Tasks
CROPs	
CCTV (closed circuit television)	Effect of changes on the process of each parameter
Control loops	Which parameters are relatively more important?
DCS synoptic displays	Comprehension of the overall process
Communication with FOP	Knowledge of the valves and switches that cannot be operated remotely through the DCS system
Alarms issued in the control-room	Knowledge of the alarms as well as start-up and shut-down procedures
Start-up and shut-down procedures with the sequence and timing of actions and commands to be taken/given	Anticipation of the consequences that might affect the process (and other units of the plant distant from the operators) subject to operator's actions and decisions. FOPs location and expected feedback from them. Communication/coordination with CROPs
FOPs	
Spatial representation hints	Detailed comprehension of allocated specific process of the plant
Olfactory hints	Spatial understanding of the subsection layout and devices/instruments/valves/switches position
Auditory hints	Comprehension of the effects of changes
Alarms in the field or coming from CROP	Relative significance of the changes on the process and possible consequences
	Anticipation of the consequences that might impact the process performance subject to operator's actions and decisions

would not be able to handle all the required tasks for physical reasons (e.g., more than one button/switch needs to be activated in a short time sequence at different sites of the plant) or because a sufficient level of safety and efficiency cannot be guaranteed (e.g., controlling various process indices at the same time that are both in the field and in the control room). For the sake of clarity, the distributed control loops in different sections of the plant and the interconnections among various components are usually scattered over a large area (for large plants common values are in the order of a few square kilometers). The interaction between CROPs and FOPs and among the agents, with the artefacts available to them in their environment, leads to the emergence of Distributed Situation Awareness (DSA).

1.3. Distributed Situation Awareness in industrial operations

The main model of Situation Awareness is Endsley's model where Situation Awareness (SA) is a three-stage process staring with perception of relevant information, secondly with understanding the importance of that information and then last, predicting the future states of the system. In short, Endsley's model of SA represents "what is going on" and "what might happen" for the human operator (Endsley, 1995). Recent research have pointed out Endsley's three-stage model is in principle an information-processing model that perceives SA as arising and being maintained inside the head of the human operator (Sorensen and Stanton, 2011). However, it has been shown recently by Sorenson and colleagues (Sorensen et al., 2011) that the Endsley model is not applicable for systems that possess multiple adaptive agents and artifacts – especially in systems where communication and coordination among the agents and artifacts are necessary for achieving desired goals (Stanton et al., 2006). This is supported by a number of authors who have argued that Situation Awareness (SA) is distributed in systems across humans and machines where a consistent coordination among them is necessary to ensure safe operations (see e.g. Sorensen and Stanton, 2011). A number of authors have argued that Situation Awareness (SA) is distributed in systems (including human and machine) and a consistent coordination among them is necessary to ensure safe operations. For instance, Stout and Salas (1998) stated that dynamic environments require a good level of SA. A failure to achieve such a level may lead to hazardous consequences (Stanton et al., 2001; Nazir et al., 2014). The distributive nature of process plants, the importance and necessity of coordination and communication among FOPs and CROPs on a regular basis (as discussed above), the co-existence of technical and non-technical personnel within different units/sections of the plant call for a greater appreciation of Distributed Situation Awareness (DSA) for industrial operators and plant owners. The idea of shared cognition (Hutchins, 1995; Stanton and Baber, 1996) and Cognitive Systems Engineering (Hollnagel and Woods, 2005), which focuses on the whole system rather than individuals within it provided the theoretical background for the theory of DSA developed by Stanton et al. (2006). The theory of DSA, according to Salmon et al. (2008, p. 369), is based on "*the notion that, in order to understand behavior in complex systems, it is more useful to study the interactions between parts in the system and the resultant emerging behavior rather than the parts themselves*".

In the process industry, safe operations are determined by the operators' ability to interpret the available information, collaborate with different teams and deal with the escalating situation based on their experience and DSA resulting from the interactions which take place within the system. The requirements for DSA intensify during an abnormal situation, as it demands that FOPs and CROPs coordinate their actions, communicate effectively and find safe solutions to conclude the escalating situation. Good communication is therefore vital in order to assure sound DSA within a system (Sorensen and Stanton, 2013). The distant location of teams within process industry increases vulnerability of team dynamics, the fragility of which is augmented during abnormal situations where procedures and guidelines may be overlooked and where decisions have to be made in a timely manner to keep the operations safe. Poor DSA can result in bad coordination, which may eventually lead to an accident where decisions go beyond the collective experience and training of the operators (Stanton et al., 2006; Nazir et al., 2014). Yet, the literature does not describe the impact of training on DSA of industrial operators. The study presented in this article, therefore, seeks to explore the impact of training on DSA.

1.4. Training of industrial operators

The operators receive training before and whilst in roles, in accordance with best practice, to ensure safe and efficient operations at industrial plants (Salas and Canoon-Bowers, 2001; Kluge et al., 2009; Nazir et al., 2013). Training is an essential component of industrial safety as it enhances the level of skills, comprehen-sion, productivity, motivation, reliability, and commitment among the trainees (Salas and Canoon-Bowers, 2001). The aim of training is guaranteeing and if possible increasing plant production while, at the same time, keeping the operations safe. The impact of train-ing on safety in the rubric of process industry has been shown by Burkolter et al. (2010), and a positive correlation was highlighted by Bouloiz et al. (2010). For team-oriented training, there has been a shift in focus from training of specific technical skills to training of general cooperation and communication skills (Helmreich et al., 1999) focusing more on the non-technical coordination of teamwork (Flin et al., 2008). Higher levels of DSA have been found to be positively correlated with team performance (Sorensen and Stanton, 2013). Moreover, there is evidence that SA training facilitates timely decisions (Saus et al., 2010) and evaluation of SA can be considered as a learning outcome of any training method (Sorensen and Stanton, 2013). The impact of training methods on performance has been investigated in several domains including medical and surgical (Aggarwal et al., 2006), mechanical systems (Peniche et al., 2011), aviation (Rupasinghe et al., 2011), driver training (Damm et al., 2011) and the military (Lele, 2013). Despite the association found between performance and training, and between DSA and performance, little research has yet sought to assess the development of DSA through training. There is need for assessing the effect of training methods on the performance and DSA of industrial operators.

This article suggests doing so through training for DSA and presents a case study of two different training methods (i.e. a conventional training based on traditional classroom PowerPoint presentation versus an advanced training in a 3D virtual-reality immersive environment). The article argues that the notion of DSA, in particular with regards to interaction, distributed cognition, and communication, should be included in training of industrial operators to foster the management of safety. An experiment is conducted to investigate the following point:

- Participants, trained with the 3D immersive environment, maintain a better Distributed Situation Awareness during an accident scenario as compared to those trained with a conventional training method.

2. Method

2.1. Participants

To assess the previous hypothesis and allow comparing the two distinct training methods, we designed an experiment based on training participants who play the role of industrial operators. A total of 24 undergraduate students (20 Males; 4 Females; age range 19–22 years; *M* = 20.8 years; *SD* = 1.03 years) from the third year of the undergraduate program in Chemical Engineering at Politecnico di Milano were recruited. The experiment was performed in accordance to the ethical standards laid down in the 1991 declaration of Helsinki. All the participants signed a consent form after receiving detailed information prior to experiment just before starting it.

2.2. Experimental design

A between-subjects design was deployed for the experiment. The independent variable was the training method (e.g., PowerPoint versus 3D immersive training) and the dependent variable was DSA.

2.2.1. Simulator set-up

The Plant Simulator™ (PS) was used in this study to simulate the whole plant and the working sites of both CROPs and FOPs (for further details see Manca et al., 2013; Nazir et al., 2013). The PS couples dynamically, and in real time, a process simulator and an accident simulator within a Virtual Environment (i.e. a 3D stereoscopic immersive environment). Technical details and benefits of training in virtual environments can be found in Rizzo et al. (2004) and Dalgarno and Lee (2010). Fig. 2 shows a schematic representation of the PS, whose features can be conceptually summarized into three parts (i.e. process simulator, 3D virtual reality engine, and accident simulator).

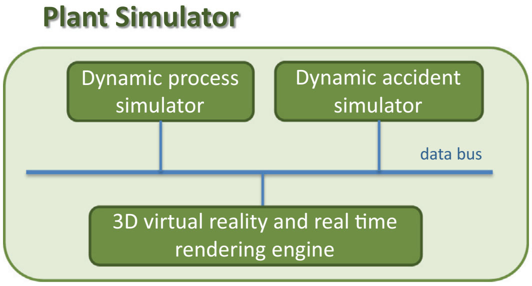

Fig. 2. Schematic representation of the Plant Simulator.

The training scenario focuses on an area of the plant that deals with the chemical process involved with separation of C3/C4 fractions. This pertains to the area where the distillation of propane and butane isomers, which are common components of crude oil, occur, within a conventional refinery. This was replicated using the UNISIM® process simulator from Honeywell (see Fig. 3a, where a 3D-engine is used to render the spatial, stereoscopic, immersive, and interactive environment). In the process industry, maintenance activities take place on a regular basis. The experiment scenario comprises an excavator that is working in proximity of the C3/C4 distillation column. The excavator of Fig. 3b hits a pipe and the collision causes the emission of a flammable liquid mix-ture. Fig. 4 summarizes the accident scenario simulated by the PS that replicates a possible and realistic situation. Further details of the process, accident, simulators, and software solution are avail-able in Brambilla and Manca (2011) and Manca et al. (2013).

2.3. Experimental tasks

All the participants to the training experiment were assigned the role of FOP, while an expert trainer performed as a CROP. This ensured that the CROP acted consistently across all experiments in terms of the information provided to the corresponding FOP and the sequence of actions that were initiated by the CROP. Every single FOP had to act according to the sequence of actions/events that are reported in Fig. 4. It is worth observing that most of the abnormal situations arising in the process industry involve coordination among CROPs and FOPs to exchange information, diagnose and mediate the situation, and take necessary actions that may mitigate further escalations of severity in the situation so to keep the system in a safe state.

Table 2 summarizes the expected correspondence (including communication, and identification of abnormalities, equipment, operating valves, instruments, and devices) by the FOP during the course of simulated experiment.

It is worth noting that the CROP messages to the FOP were the same for all the participants to the experiment. The operation on the valves and switches (either in the control room or in the field) was assumed consistent and effective only if the communication between FOP and CROP was based on precise and timely instructions. The communication intensity and criticality escalated during the accident scenario. Indeed, a slight delay or miss of communication can hinder the safe operation, thereby increasing the possible damages/consequences of the evolving accident. Clearly, without the communication exchange, illustrated in Table 2, it would not be possible to resolve the accident scenario reported in Fig. 4.

2.4. Training sessions

The 24 participants were divided into two groups of equal size. The participants had neither any previous experience with the

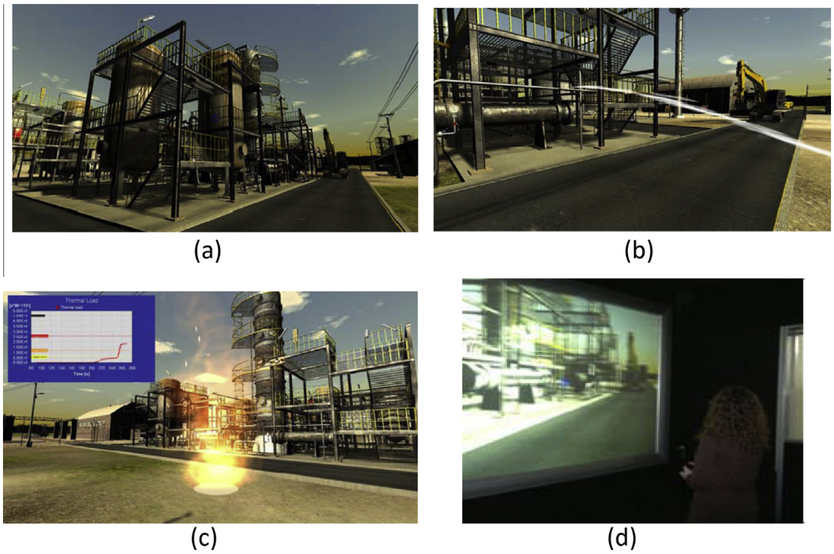

Fig. 3. (a) 3D representation of the C3/C4 separation section; (b) liquid jet after the rupture of a flange; (c) pool fire; (d) a participant performing the experiment (images courtesy of Virthualis company).

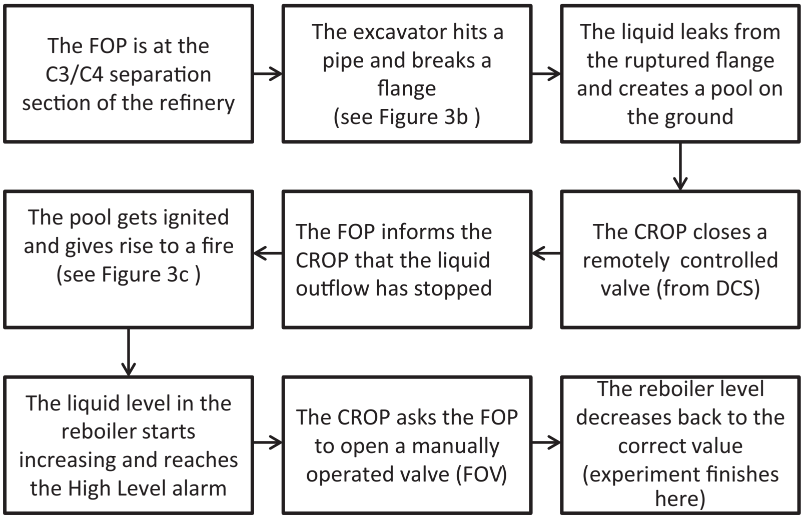

Fig. 4. Sequence of events simulated in the virtual experiment.

Table 2
Example of expected communication between Control Room Operator (CROP) and Field Operator (FOP) during the experiment.

FOP communication to CROP	CROP communication to FOP
The excavator just hit a pipe. We have a liquid leakage from the flange after column T-101, T-101	Waiting for further information
We have a liquid pool that spreads on the ground. The damaged flange is on the bottom line from T-101, T-101	
I suggest closing valve LV-104, LV-104	
	I am going to close LV-104, LV-104
	Valve closed. Can you confirm that the leakage is over?
Control room, this is field operator. The liquid outflow from the flange is completely over	
Control room, the pool got ignited! We have a pool fire. Please alert Fire-fighters at T-101, T-101	Fire-fighters alerted
	Field operator, this is control room. Please open FOD-103, FOD-103
Roger. I am going to open FOD-103, FOD-103	
Control room, FOD-103, FOD-103 is completely open. Can you confirm the operation?	
	Field operator, this is control room. The liquid level in the reboiler of T-101, T-101 is going back to normality

training environment nor any experience of working as operators at industrial plants. The two groups were given names according to the selected method of training respectively.

2.4.1. 3D Group

The first group was trained using directly the 3D immersive environment and was identified as the “3D Group”. The participants of this group were provided with 3D glasses for immersive experience (Fig. 5a). However, the spatial sounds emitted by the virtual equipment were disabled, to avoid the involvement of auditory input senses. All the participants were volunteers who had joined the experiment as a response to an advertisement made at the Chemical Engineering department of Politecnico di Milano. There were 12 participants in the 3D Group had the mean age of 21.1 (*SD* = 1.08) and they were given IDs from 1 to 12. The participants arrived at the experimental facility. Before taking them to the virtual reality room, they were given a brief background about the nature of the chemical process, general tasks, and expectations from the operators during normal and accident situations. We ensured that none of the participants had any phobia of immersive environments and that each of them was comfortable with 3D glasses. For the sake of detail, we used 3D passive glasses that have a much lower impact on the user in terms of possible equilibrium troubles. The participants of 3D Group were then taken to the virtual reality room. The total training time was 45 min.

2.4.2. Conventional Training Group

The second group was trained with a conventional training method (i.e. PowerPoint presentation). This group was identified as the Conventional Training Group and had 12 participants with mean age of 20.8 (*SD* = 1.03). The participants were provided with 3D still images taken from the virtual reality environment and shown through a slide presentation (see Fig. 5b). The participants of this group were assigned an ID from 13 to 24. A brief introduc-tion to industrial accidents and safety critical situations was given to all participants without signaling the possible accident scenario that they would encounter in the experiment. The total training time for CT Group was 45 min.

Arrangements were made to keep the groups separate from each other to avoid any exchange of information. Moreover, we attempted to keep the time difference between the training and actual experiment on the Plant Simulator at a consistent level for all the participants. In addition, the homogeneity among the participants, as they were all students from the same semester, the difficulties of age difference, background diversity, and communication did not emerge.

2.5. Data analysis

2.5.1. Performance assessment

Once trained, the participants underwent an assessment procedure to measure quantitatively the learned skill of dealing proficiently with abnormal situations according to their understanding of the process in terms of operations, equipment, measuring devices, and actuators. To make the assessment unbiased and therefore independent of human predispositions and/or errors by the trainer or assessor, an automated assessment procedure was adopted (Manca et al., 2012). The performance of the operator was recorded in real time by a dedicated algorithm implemented in a computer program that measures and assesses most of the indicators that contribute to DSA as a function of the simulated scenario. Some other indicators were recorded manually and post-processed aseptically to extract further bits of information about the performance of the operators. Fig. 6 shows the perfor-mance indicators devised for the simulated accident scenario. At the end of each experiment a personal log file was generated. The performance indicators, which describe and measure the DSA of operators in the simulated scenario, are named as Distributed Situation Awareness Indicators (DSAIs).

The observed DSA depended on the effective communication between the FOPs and the CROP, their extraction of information from the plant equipment, and their understanding of the evolving situation during the accident scenario. Therefore, the performance parameters as measured by the FOPs performance were considered in the light of the theory of DSA (Stanton et al., 2006).

2.5.2. Distributed Situation Awareness Indicators

The DSAIs (i.e. Distributed Situation Awareness Indicators) devised for the experiment are based on the evolution of the situation that unfolds after the initiation of the abnormal situation which is triggered by the excavator that hits the pipe. Therefore, the first expected action taken by the FOP should be to identify the collision and observe the leakage without delay (i.e. the first DSAI of Fig. 6). Once the information has been communicated by the FOP, the *baton* is passed on to the CROP who calls the closure of a manually-operated valve. When the CROP calls the field oper-ated closure of the valve, the FOP must be capable of identifying that device (i.e. the second DSAI of Fig. 6). Meanwhile, the leakage of flammable liquid accumulates on the ground and creates a pool (as shown in Fig. 3c). The maximum pool diameter (i.e. the third DSAI of Fig. 6) sets out the highest amount of liquid accumulated before the participant is able to respond to coordinate the leakage stoppage (without doing so the accident would escalate significantly). The amount of liquid in the pool defines the intensity and persistency of the fire, which afterwards gets ignited as reported in Fig. 4. Subsequently, the next DSAIs are respectively the identification and reporting of the fire, and the maximum flame height observed by the FOP. The impact of fire can be judged by the flame height (being the radiative flux proportional to the pool diameter and the flame height). Different equipment and devices are located very closely in the process industry. Therefore, a higher flame increases the likelihood of damage to surrounding equipment and hence the escalation of the accident scenario.

(a) Training of the 3D Group by3D

(b) Training of CT Group by slide-

Fig. 5. (a) Training of the 3D Group by 3D immersive observation. (b) Training of CT Group by slide-supported classroom lesson.

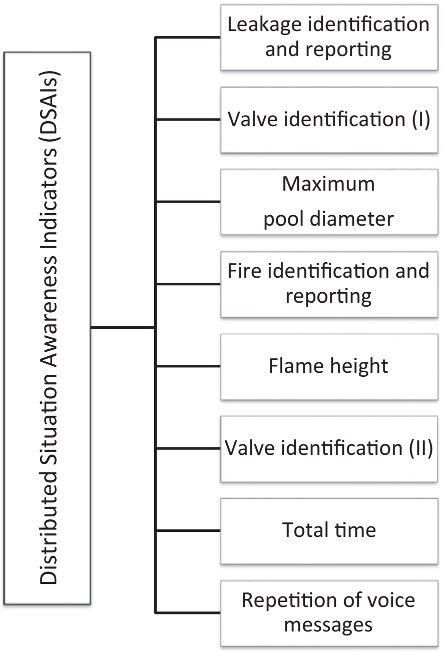

Fig. 6. DSA indicators (i.e. DSAIs) for the performance assessment in the simulated experiment.

In the simulated experiment the need for information moves dynamically to and fro the FOP and CROP, and depends on several process features. In accordance with the notion of DSA, the coordination of actions, communication between the CROP and FOP, their respective interaction with non-human agents and flow of information enable DSA to emerge as a systemic property.

Significantly, the understanding of the evolving scenario depends on the knowledge and information available to each agent in the process industry, e.g., the system, and neither of the CROP or FOP can resolve the situation independently of the other. The coordination of activities sees the *lead* move between the FOP and CROP with both requesting information and decisions of the other when *in charge*. When the CROP holds the leading position the FOP takes on the function of a collaborator and vice versa when the FOP assumes the leading position. It is clear, therefore, that the skills required by both FOPs and CROPs are as much non-technical as technical, warranting a training focus on the factors which contribute to the emergence of DSA (e.g., interaction between the parties, coordination of actions, and communication). By doing so, the safety of the plant and the effective management of accident scenarios can be assured.

As shown in Fig. 4, the identification of the valve in the field, contributes to the understanding of the status of the process held by the FOP, which therefore becomes an indicator of the DSA which has emerged. Similarly, the total time taken by the participant to perform the necessary steps (with reference to Fig. 4 and Table 2) gauges his/her understanding and capability (i) to execute the actions that are based on the communication/coordination with the CROP, (ii) to handle various artifacts involved in the experi-ment (e.g., valves, levers, switches, walkie-talkie).

Repetitions of voice messages were recorded during the course of experiment. It was assumed that better communication would reduce the need for repetition(s) of voice messages. Repetition of voice messages was the only DSAI that was registered manually.

All the reported indicators can also be of real help in assessing the overall performance of operators. However, the current study aimed to assess the DSA of operators resulting from two different means of training. It was expected that the response of participants may be affected by the type of training received. This study hypothesized that 3D immersive training in a virtual environment can facilitate and improve the DSA of operators in comparison with conventional training methods such as those based on PowerPoint presentation.

3. Results

The results obtained for the DSAIs discussed above are reported according to their sequence shown in Fig. 6.

3.1. Leakage identification and reporting

Fig. 7 shows the number of participants that correctly identified and reported the leakage among the 3D and CT groups. A total of 67% of participants of the 3D Group were able to identify and report the leakage, whereas only 42% of the participants in the CT Group were successful.

3.2. Valve identification (I)

The successful number of participants for identification of valve I was 10 for the 3D Group as compared to 6 for the group that received CT Group (see Table 3 and Fig. 7).

3.3. Maximum pool diameter

The average value of maximum pool diameters for the participants of 3D Group ($M = 1.56$ m, $SD = 0.39$ m) was about 60% smaller than that of CT Group ($M = 1.97$ m, $SD = 0.42$ m). The difference was found to be statistically significant ($M_{\text{diff}} = -0.404$ m, $t_{22} = -2.455$, $p = 0.022$, 95% *CI* of difference [-0.745 m, -0.063 m], Cohen's $d = 1.0$) and of practical significance as a larger pool diameter of flammable liquid increases the possible risk of a pool fire.

3.4. Fire identification and reporting

The successful number of participants for fire identification was 10 for 3D Group as compared to 6 for CT Group (see Table 3 and Fig. 7).

3.5. Maximum flame height

The 3D Group ($M = 4.27$ m, $SD = 0.88$ m) obtained a 40% smaller average maximum flame height than CT Group ($M = 5.95$ m, $SD = 1.24$ m). The difference between the two groups on maximum flame height was statistically significant ($t_{22} = -3.845$, $p = .001$, $M_{\text{diff}} = -1.69$ m, 95% CI of M_{diff} [-2.60 m, -0.78 m], Cohen's $d = 1.57$) and the effect size was large according to Cohen's classification of small ($d \leqslant 0.2$), medium ($d \approx 0.5$) and large ($d \geqslant 0.8$) effect sizes (Cohen, 1992).

3.6. Valve identification (II)

Only half of the participants (50%) of CT Group were able to identify valve II, while the 3D Group outperformed them with a success rate of 75%.

As can be seen in Table 3, 3D Group (i.e. the group trained in a 3D immersive virtual reality environment) was able to identify more leakages, fire, and manually operated valves.

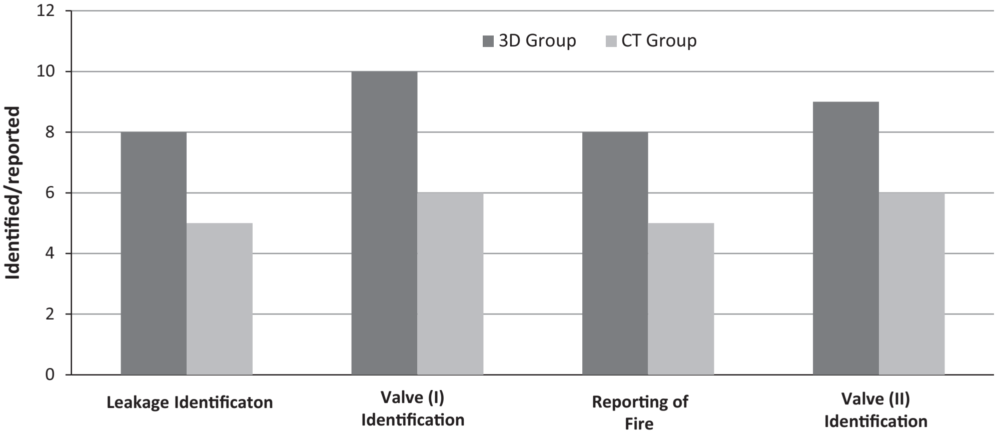

Fig. 7. Number of participants of 3Dand CT Groups who identified correctly the leakage, valve I, reported fire, and identified valve II (higher is better).

Table 3
Number of correct identifications for the two training groups.

Object of identification	Groups		Statistical comparisons		
	3D Group	CT Group	*U*-test[a]	*p*[b]	*PS*[c] [95%*CI*][d]
Liquid leakage	8/12 (67%)	5/12 (42%)	54	.229	.63 [.42, .83]
Fire	8/12 (67%)	5/12 (42%)	48	.229	.63 [.42, .83]
Valve I	10/12 (83%)	6/12 (50%)	48	.090	.67 [.50, .83]
Valve II	9/12 (75%)	6/12 (50%)	54	.216	.63 [.46, .79]
Total identification (*M*, *SD*)	2.92 (1.24)	1.83 (1.34)	38	.051	.70 [.49, .88]

[a] U-test refers to the non-parametric Mann-Whitney *U*-test.
[b] Two-tailed asymptotic significance.
[c] *PS* = 'probability of superiority' (see Grissom and Kim, 2005, pp. 149–165). *PS* is calculated as *Pr 3D.* [d]
Confidence interval for PS is calculated using a bootstrapping procedure resampling 10,000 times.

3.7. Total time

The time taken to resolve the accident scenario reflected the responsiveness and attention allocation skills of the operators. The shorter the time taken the more precise the communication and the more timely the information flow between the CROP and FOP and the less severe the consequences produced by the accident event (as far as the requested actions are consistent and correct). The participants of 3D Group (Mean duration = 247.6 s, *SD* = 52.1 s) used on average 50 s less time than the participants of CT Group (Mean duration = 297.6 s, *SD* = 44.1 s) as measured by an independent samples *t*-test ($t_{22} = -2.535$, *p* = .019, 95% *CI* of mean difference [−90.8 s, −0.09 s], Cohen's *d* = 1.04) indicating a large effect size observed in terms of reduction in time as a function of training methods. For instance a 25 s delay in reporting the leakage (average flow rate 0.25 kg/s) of flammable liquid (in case of this experiment) would result in more than 6 kg of additional release. Similarly, a delay in the last step of the simulated experiment, which requires the FOP to open a valve as suggested by the CROP, would accumulate more liquid in the reflux drum and consequently would increase the risk of flooding and outflow (with possible explosion in case of ignition of the emitted overheated liquid).

3.8. Repetition of voice messages

Measures of communication indicated that the 3D Group (*M* = 0.33, *SD* = 0.49) asked for fewer repetitions of voice messages than the CT Group (*M* = 0.75, *SD* = 0.97). Four of the participants of the 3D Group needed one repetition of voice message from the CROP. Conversely, a total of five participants of CT Group required a repetition each of voice messages for their complete comprehension and four of them required an additional repetition of the message to understand it completely. Whilst requiring repetitions of the information could have huge practical effects in a real crisis situation, as the repetitions would take more time, the observed difference was not statistically significant as measured by a non-parametric Mann-Whitney test (*U* = 58, *df* = 22, *p* = .443 (two-tailed test), *PS* = .40, 95% *CI* of *PS* [.21, .61]). A statistical significance was found, however, for the 3D Group (*M* = 8.42, *SD* = 0.9) ability to recall the voice messages, compared to the CT Group (*M* = 6.92, *SD* = 1.56, *U* = 26, *df* = 22, *p* = .005 (two-tailed test), *PS* = .82, 95% *CI* of *PS* [.64, .96]).

4. Discussion

This study examined the impact of training methods on the DSA that emerged from the interaction between FOP and CROP by comparing indicators of DSA during a simulated accident scenario.

The training typology did appear to have an effect upon the emergent DSA of the operators. It was clear that the 3D Group performed better on the DSAIs when compared with the Conventional Training (CT) Group.

The idea of improvement in individual SA with training has emerged in recent years (Saus et al., 2010). This study has shown that the improvement in DSA can be associated with a specific training method. The 3D spatial environment allowed the participants to achieve and maintain a better DSA and to do so comparatively faster than the CT Group. This study has reinforced the finding that a better DSA improves performance of workers in process operations (Sorensen and Stanton 2013; Stanton et al., 2006). Moreover, the findings emphasized that during an abnormal situation the impact of the DSAI increased manifold and that better trained operators were more likely to be able to maintain sound

DSA. For example, the 3D Group performed consistently better than the CT Group in all the events of the simulated accident. A good level of DSA allows the operators dividing their attention timely with respect to the dynamics of the evolving situation and seamlessly communicating the necessary information to the most relevant team member(s) located in different/distant locations at the right time (Patrick and Morgan, 2010).

In the simulated experiment, the communication between FOP and CROP was of vital importance in mitigating the impact of accident. An evolving and continuously updated understanding of the situation was necessary to execute appropriate actions (e.g., identifying/locating correct valves, opening or closing a valve). As has been suggested elsewhere, individual SA would not be sufficient to overcome the difficulties arising in the abnormal situation (Patrick and Morgan, 2010).

One implication of this study is the importance of designing training methods by incorporating features that may facilitate the emergence of DSA especially during non-routine tasks and abnormal situations. Modifying already designed and operating chemical plants to further improve the process safety would be unfeasible in most cases due to the well-defined control loops, boundary conditions, and equipment. An improved training methodology, however, can be a feasible and economical step in improving the process safety and mitigating the number and consequences of accidents. In addition, 3D immersive environments used to train the operators in case of a possible accident scenario increase the likelihood that DSA emerges and can be maintained. Whilst the two training methods were found to differ, both had a positive impact on the emergence of DSA. However, the immersive environment resulted in the greatest rewards with respect to the DSAI assessment. On the other hand, the limitation of conventional training methods, for instance, lack of immersivity, spatial learning, emotional engagement, and unavailability of the *whole picture* are some of the elements that can be cautiously attributed to their worse performance respect to 3D Group.

Improvement in performance, based on training methods, has been proposed among others by Salas and Canoon-Bowers (2001), Burkolter et al. (2010) and Kluge et al. (2009). Their findings have been reinforced with this study.

The findings presented here are also in accordance with the study of Patrick and Morgan (2010) as evolving dynamic events require the exchange of information with subsequent actions among team members located at geographically dispersed locations. This study showed that the quality of communication between FOPs and CROPs underlies the emergence of DSA, as was demonstrated by Sorensen and Stanton (2013). The findings of Bouloiz et al. (2010), which report a positive correlation on safety with respect to the quality of training, support the outcomes of current study (see also Section 3). The indicators for DSA were devised in line with the concepts presented by Stanton et al.(2006) and Salmon et al. (2009). These emphasize the distributed nature of SA among different elements in a system, including humans and the artifacts they utilize. During an accident scenario the situation changes quickly and its development depends on the nature of the accident. Clearly, the safety of the system, manage-ment of the developing situation and resulting outcomes of the accident scenario depend on the timely and accurate conveyance of information from the FOP to the CROP and vice versa. Communication therefore influences the overall safety performance (Sessa et al., 1999).

Whilst the findings presented here confirm the association between DSA and performance and between training and performance, some limitations regarding this study should be pointed out. First, the participants were students and not real industrial operators, thus they did not represent the actual population of target users of the Plant Simulator. However, the participants were chemical engineering students having a common background and knowledge of chemical processes, and relevant terminologies, thus they showed close similarities to the potential users of the Plant Simulator. Second, the generalization of this study needs further investigation and efforts by the relevant scientific community. Moreover, the assessment was conducted in a 3D environment and not at the real plant. It was evident that simulating an accident scenario in a real environment would be impossible as it would demand a significant amount of resources and would involve an unacceptable risk to safety. Finally, the simulated environment was limited to a subsection of a refinery. In a real plant the operator might be saturated with more information, numbers, and data that can convey further confusion and miscommunications. This fact, however, highlights the importance of appropriate training given the positive results revealed here for the emergence of DSA and associated performance.

5. Conclusions

Automation and technological developments have made the job of industrial operators easier in terms of physical efforts but also more complex and challenging in terms of cognitive load, attention allocation, awareness, responsiveness, and mental effort. The safe operation of a plant, the probability of malfunctions, abnormal situations, and accident scenarios often depend on the decisions made by a number of operators working in a coordinated manner despite being geographically dispersed. Better DSA ensures coordination and facilitates sound decisions, thus resulting in the continuous running of the process with reduced or even negligible consequences stemming from abnormal situations, near misses, and accidents. The experiment presented and discussed in this article showed that 3D immersive training methods in the process industry can provide improvements in DSA above and beyond those seen when a traditional training method is used. This study highlighted the importance of DSA for industrial operators but also paved the way towards improving DSA with well-developed training methods. The focus of this study was on understanding the impact of different training methods on the emergence of DSA and the safety of the process. While these early findings are promising, further studies are necessary to exhaustively investigate: the relation between training and DSA, the possible improvements in the training methods presented in this work, the optimal frequency and duration of training, and, to explore the pros and cons of developing DSAIs for various scenarios.

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