Benefits and impact of emergency training in a VR environment

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Abstract

This study addresses the critical need for realistic emergency training in industries where non-stationary conditions can quickly escalate into accidents or incidents. Real-life training is often impractical due to safety concerns and cost constraints. Consequently, incorporating immersive technologies into training curricula becomes crucial. This research explores participants' self-reflection on safety readiness during virtual reality (VR) emergency training and investigates the impact of interactive versus passive exposure to emergency situations in VR.

Three distinct exposure methods were developed, varying in the degree of participant involvement. Surprisingly, no statistically significant differences were found among the groups, indicating a positive perception of VR emergency training regardless of the exposure method. Participants valued the opportunity to safely make mistakes, witness consequences, and repeat procedures in VR. They believed such training enhanced their real-life emergency responses by fostering calmness, quick thinking, and prudent reactions.

However, some participants expressed skepticism, suggesting that VR training might not accurately simulate real-life stress conditions. Future research should explore the impact of photorealistic VR experiences on operators' perceptions and assess the benefits of additional efforts in VR development for emergency training.

1. Introduction

Training in non-stationary conditions is crucial to prepare the operators to handle rapidly developing unexpected situations, as these conditions could evolve into accidents or incidents very quickly [1]. It would be ideal to have the possibility to create these situations during the training in the plant. However, there is a lack of realistic training when it comes to emergency situations in the industry. This type of training cannot be done in real life to its full extent as it may be too dangerous or not possible to perform, and very expensive to organize or reproduce [1,2,3]. For those reasons, it is purposeful to include emergency training in the current curricula with the support of immersive technologies, given the importance of the training and the benefits of the technology [1, 25].

It is possible to recreate a dangerous situation in the virtual world allowing the operator to experience the consequences of unsafe behaviour, mistakes in a procedure, unexpected process upsets due to, e.g. technical failure. The opportunity to conduct experiential learning with hazardous and abnormal situations could help operators to acquire a better understanding of the process and train for swift and adequate responses to process deviations and emergencies [4]. Moreover, the experience could trigger psychological pressure on the operator and provide the possibility to learn how to handle these situations in those conditions [5].

Srinivasan *et. al.* [6] highlighted that as it is not possible to recreate an emergency situation in reality, it is impossible to predict the human response when they are presented with a real dangerous situation. Those situations can cause panic and unexpected behaviour, preventing the operators from "acting rationally and safely". As Trevor Kletz [7] pointed out: "It is not, of course, sufficient to have knowledge. It is necessary to be able to apply it to real-life problems".

The purpose of this study is to explore the self-perception of the participants on safety readiness when exposed to emergency situations in a virtual reality training. Secondly, it is relevant to explore the effect of the way of exposure (i.e. interactive versus passive) of the participants to emergency situations in VR. Is it sufficient to only show the consequences of incorrect actions or should the participants be required to solve the emergency in order to increase their confidence in dealing with future emergencies?

To better understand this topic, the research questions that guided this study were: How does the possibility to experience or solve an emergency situation change the perception of readiness to an emergency situation on the workplace? And how does the mode of exposure to an emergency situation impact on the participants' perception of preparedness to deal with real emergencies?

2. Materials and methods

2.1. Participants

The participants were divided into three groups of 23 participants each. All the participants were experienced operators from the chemical company Merck KGaA, Germany. The participants were invited to a time slot of 1.5 hours. The study took place during working hours. The fact that the experienced operators in the German chemical industry work in a shift system was considered. For this reason, no time slot was allocated during the change of shift. Two-time slots (in two different rooms) were conducted in parallel. One researcher was in each study room. The participants were welcomed to the study rooms by the researchers. As the experienced operators came from two different plants, they were distributed evenly in each study room to avoid one researcher always receiving participants from the same chemical plant. The data was collected over a period of 5 weeks. As the participants arrived, they were informed about the activities of the following 1.5 hours in the study (Figure 1). The participants received, read and signed an information sheet and the consent form. Then the participants filled out a pre-VR questionnaire and they were introduced to the virtual reality hardware required to interact with the VR training “Operate Your Own Reactor”, which is described in the next subsection. They familiarized themselves with the controllers, read and follow the instructions displayed by the head-mounted display. These instructions provided all details for how to interact and navigate in the environment. Once these instructions had been followed, the participants were instructed to begin the “Operate Your Own Reactor” training. They were told that they had the option to take breaks throughout the training after each step. The system displayed a question reminding them of this option at the end of each step and the participant could decide if they wanted to take it or continue. Once the participants completed the virtual reality training, they were asked to complete a post-VR questionnaire.

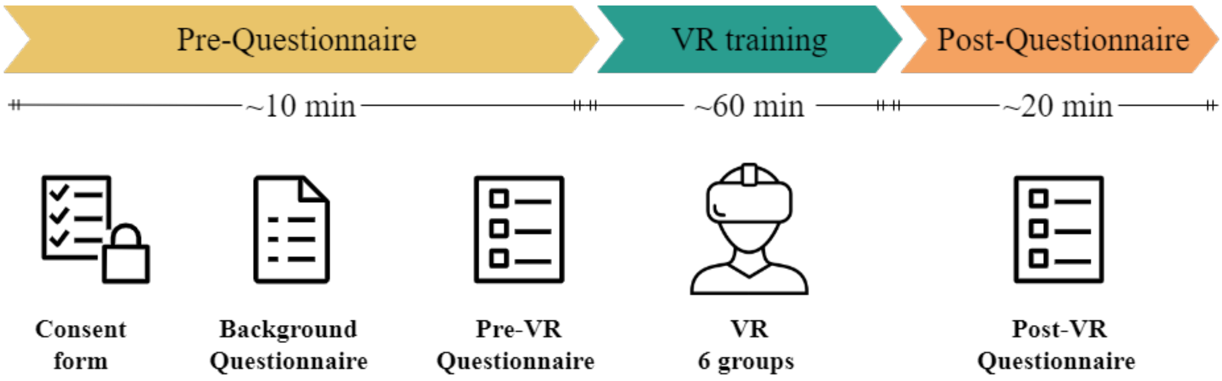

Figure 1. Outline of the activities of the day and the order of questionnaires.

2.2. The VR Prototype

The study was performed with the "Operate Your Own Reactor'' version 2.0 VR [24]. The Standard Operating Procedure (SOP) includes the main stages of commercially producing n-butyllithium (BuLi) (excluding only cleaning of the batch reactor at the end of the reaction). The stages are: (i) preparation of the reactor, (ii) setup and raw materials batching, (iii) reaction, and (iv) extraction of product. All participants went through the four stages of the production process. Besides the execution of the Standard Operation Procedure, the participants could experience an emergency situation or not.

2.2.1. The implemented emergency situations

A simplified Hazard and Operability Study (HAZOP) as conducted to systematically identify and evaluate the possible problems that may represent a risk for the personnel or equipment when commercially producing BuLi. Three situations are selected and implemented in the prototype, based on the recommendation of experts considering, among other factors, which would be the most enriching situations to include in VR training.

1. Dosing quantity of the reactant chlorobutane (ClBu) too high during reaction. This emergency situation takes place in step iii – Reaction. The SOP indicates that the operator needs to add ClBu in two steps, first with an IBC of 70 kg and later on with an IBC of 300 kg. In this emergency, it is assumed that for some reason the first addition of ClBu is higher than 70kg. Possible reasons are: taking an IBC with a wrong label and not using the scale to verify, technical problem with the scale such that

the verified weight is incorrect (underestimation); or making a human error by mixing up the dosing steps (instead of starting with 70 kg, the operator starts with 300 kg). When this erroneous dosing occurs, the chemical reaction will have a much higher exothermic potential, and this will lead to a series of events. (i) Increase in pressure and temperature in the reactor vessel; (ii) high-pressure alarm and high-temperature alarm; (iii) hearing of vibrations related to the boiling of liquids inside pipes and reactor; (iv) activation of relief valve (very noisy) when too much ClBu has been added; (v) Loss of containment due to equipment integrity loss: pipes and condenser rupture, and release of BuLi to the atmosphere, evaporation of solvent and contact of BuLi with air; (vi) BuLi as a pyrophoric liquid: catches fire spontaneously if exposed to air; (vii) explosion and fire. Once the violent exothermic reaction has started, the operators must evacuate immediately and notify the emergency personnel, but there is no action that they can take to remedy the situation. Possible prevention steps are: the amount and timing of the dosing of each substance are explained in an SOP; check-in 4-eyes principle with a check-list (which involves two individuals reviewing and confirming critical steps such as verifying the dosing); use two different scales for the measurement of the weight and weigh twice before adding into the reactor.

2. Loss of cooling during reaction. This emergency situation also takes place in step iii – Reaction. It occurs due to a technical failure or malfunctioning of the cooling system. The temperature will start rising inside the reactor, and this is observable on the control screen. Simultaneously an alarm will start sounding and red flashing warning lights can be observed on the cooling system control screen. The emergency will start when the operator is adding ClBu. If the operator does not stop the addition of the reactant, the physical observations in the chemical plant are similar to the ones reported in #1 "Dosing quantity reactant ClBu too high": inside the reactor, there will be a chemical reaction with much higher exothermic potential than planned, that will evolve into a violent temperature and pressure rise in the reactor. This will lead to the loss of integrity of the reactor and pipes, followed by fire and explosion of the reactor. To remedy the situation the operator needs to stop the addition of ClBu to the reactor. For this there are two possible ways: (i) closing valve manually; (ii) closing valve from the control screen.

2.3. Exposure route to emergency within VR

Three different means of exposure to emergency situations were developed.

Group "No emergency": This version only included the standard operating procedure (SOP) for the commercial production of n-butyllithium.

Group ``Emergency SEE'': In this version emergency situation #1: "Dosing quantity reactant ClBu too high" is included. In this situation it is assumed that for some reason the first addition of ClBu is more than the weight indicated in the SOP. Possible reasons are: taking the wrong input in kilograms; taking an IBC with a wrong label and not using the scales to verify, technical problem with the scales such that the verified weight is incorrect (underestimation); or making a human error by mixing up the dosing steps (instead of starting with 70 kg, the operator starts with 300 kg). It is not possible to solve this situation, and the participant sees the consequences of this situation arising, while in real life their only action would be to evacuate the area. In the VR situation, it is possible to see the developing scenario followed by the explosion and destruction of the reactor. After the simulation of the emergency ended, the participants were presented with a "new batch reactor" and continued with the SOP.

Group "Emergency SEE and SOLVE": First, the participant sees the consequences of emergency situation #1: "Dosing quantity reactant ClBu too high" and a new batch reactor is started after the emergency situation, is equivalent to Group "Emergency SEE". While continuing the SOP on the newly started batch process the emergency situation #2: "Loss of cooling" (SEE+SOLVE) starts to develop. Here, the participant has to solve the situation. Their response time is limited to 2.5 min. If the participant has no idea how to solve the situation, a hints system provides progressive hints. The system was designed in a way that the operator has time to think and respond before receiving the option to ask for a hint.

Hints system: the main screen included a bar timer that showed how much time the participant had left to solve the situation and they were instructed that if they did not know how to solve the situation, hints would be provided soon (see Figure 2), translation "If you do not know, you will soon receive instructions."). Three hints were provided progressively:

1- Hints on the problem: red alarm on ALAC1 indicates that the cooling system (ALAC1) has failed. The temperature of the reactor is rising.

2- Hints on the solution: you must stop the addition of Chloro-butane (ClBu) to the reactor.

3- Solution: to close the connection at the inlet of the reactor, click on ACA71 and then on “EXIT”. Or close the valves of IBC2 on the 3rd floor.

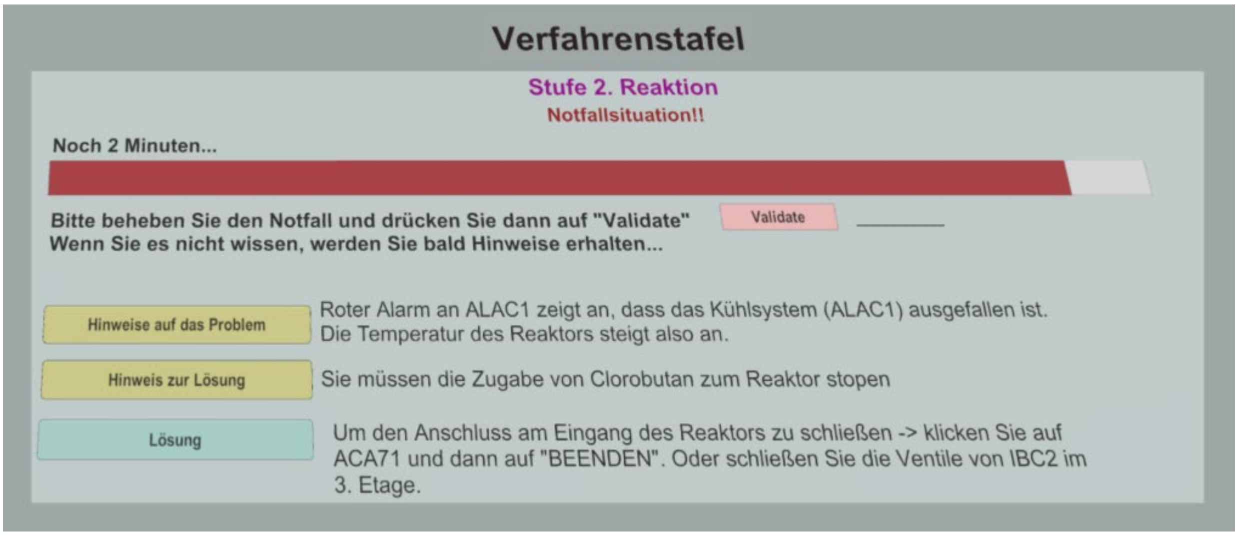

Figure 2. Emergency screen with hints presented to the participants. The red bar progressively increases as time passes. The three hints appear progressively, after the participant requests them by clicking in the buttons of the right.

2.4. Measurements

At the end of the virtual reality experience, each group completed a questionnaire about their opinion and experience with virtual reality training. To gain understanding of the self-perception of participants regarding their readiness to handle an emergency situation in real life, two Likert-scale questions (5-point scale) followed by an open-end question (“Why did you choose this rating?”), were presented to them. Both questions were compulsory to answer. As the three groups received three different exposures to emergency situations, the headings of the questions were slightly modified for each group (Table 1). The two questions can be found in Table 2

Table 1. Headings for the three groups to set the view before the questionnaires.

Group	Heading
“No Emergency”	Imagine that the virtual reality that you have just experienced includes an emergency situation, in which you can see the consequences of an accident and take actions to solve the problem.
“Emergency SEE”	Imagine that the virtual reality that you have just experienced includes an emergency situation, in which you can not only see an emergency, but you can also take actions to solve the problem.
“Emergency SEE+SOLVE”	-

Table 2. Questions for the self-perception of participants regarding the readiness to handle an emergency situation.

Question #5	How much do you think that having experienced an emergency in the virtual reality would help you in being more prepared in the future for an emergency in the real plant? I think the virtual reality would: 1. Not help me at all 2. Not help me 3. Somewhat help me 4. Help me 5. Help me a lot
Question #6	How much do you think that having experienced an emergency in the virtual reality training would help you learn how to behave in a future emergency in the real plant? I believe practicing in virtual reality would: 1. Not help me at all 2. Not help me 3. Somewhat help me 4. Help me 5. Help me a lot

2.5. Statistical analysis

The statistical software Minitab 21.1 was used for the analysis. For the Likert-scale analysis, the most appropriate method as a measure of central tendency is the median. In addition, as the scores of a Likert scale are discrete values not normally distributed, a non-parametric statistical test must be used. The Kruskal-Wallis test is employed to determine whether the median of the three groups differs from each other [8,9].

For the open-ended question, the software NVivo (from QSR International) was used to analyse the responses in the original language (German), using an inductive thematic analysis to identify codes and themes [10]. The thematic analysis allows for the classification of responses, summarizing the topics in a structured approach. In an inductive thematic analysis, the process of coding takes place “without trying to fit the responses into a pre-existing coding frame” [11].

3. Results

The participants were asked to what extent they think experiencing an emergency situation in virtual reality would help them in **being more prepared** (question #5) or **learn how to behave** (question #6) in an emergency in the real plant. The responses were analysed by comparing the responses of the three groups: a) “No emergency”, b) “Emergency SEE”, and c) “Emergency SEE+SOLVE”. It is important to highlight the different context for the group responses. All the replies of group “a) No emergency” are based on them imagining the scenario, as they received a version with no emergency (see Table 1). They are providing their opinion based on a hypothetical assumption only.

3.1. Findings from qualitative analysis

As can be observed in Figure 3 for question #5, the median of the response of group “no emergency” equals “3-Somewhat help me”, while for groups “emergency SEE” and “emergency SEE+SOLVE” it equals “4- Help me”. The test for the medians showed that despite the slight differences in the distributions for each of the groups, as indicated by the box plots, there is no statistically significant difference between the medians of the three groups (Kruskal-Wallis, $p=0.310$).

For question #6, Figure 4 shows that all the medians are equal to “4- Help me”. The test for the medians, showed (as expected and despite the slight differences in the group distributions) that there is no statistically significant difference between the medians of the three groups (Kruskal-Wallis, $p=0.647$).

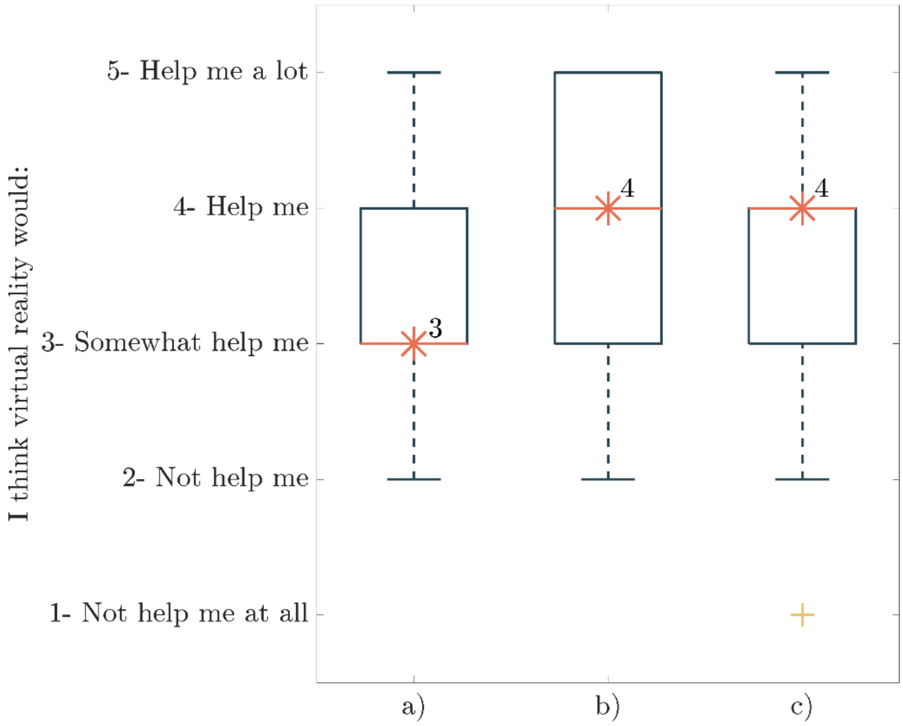

Figure 3. Box plots of the answers to question #5: "How much do you think that having experienced an emergency in the virtual reality would help you being more prepared in the future for an emergency in the real plant?". a) No emergency, b) Emergency SEE, c) Emergency SEE+SOLVE. Participants: $n^{a)}$=23, $n^{b)}$=23, $n^{c)}$=23. The asterisk circle indicates the median.

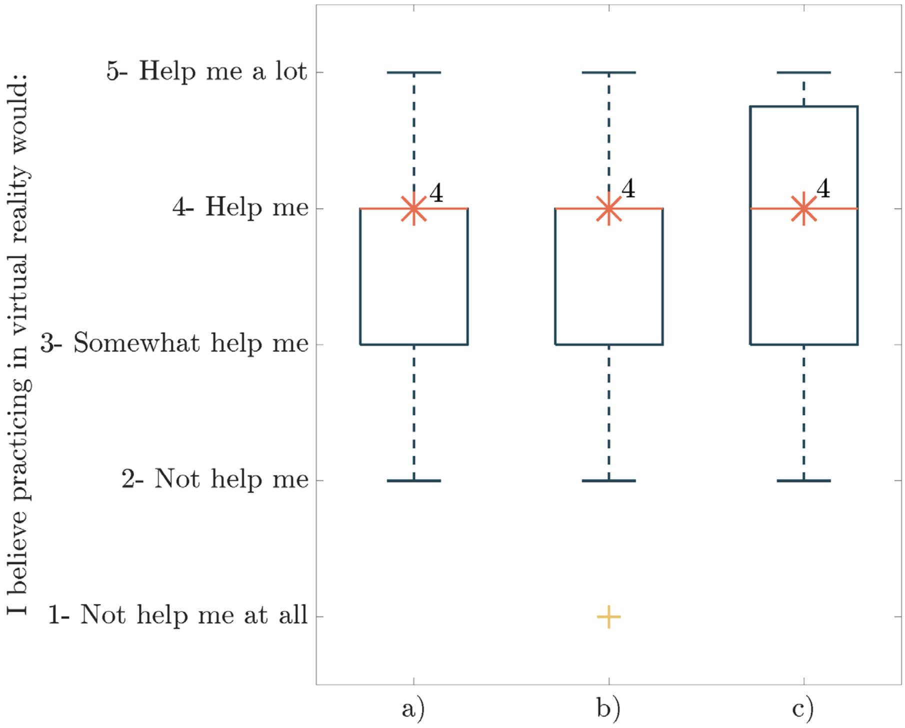

Figure 4. Box plots of the answers to question #6: "How much do you think that having experienced an emergency in the virtual reality training would help you learn how to behave in a future emergency in the real plant?". a) No emergency, b) Emergency SEE, c) Emergency SEE+SOLVE. Participants: $n^{a)}$=23, $n^{b)}$=23, $n^{c)}$=23. The asterisk circle indicates the median.

These results indicate that regardless of the participants experiencing (either passively or actively) or not experiencing an emergency situation at all in virtual reality, their opinion on how useful they found emergency training in VR in order to be more prepared or to learn how to behave in case of a real-life emergency does not change.

Although no statistical differences were found among the medians of the groups, some observations can be made from the distribution of the responses. For this, a more detailed representation of the data is shown in Figure 5 and Figure 6, for question #5 and question #6, respectively. From the plots, it can be seen that the large majority of the three groups have a positive opinion of the help that emergency situations in VR can provide in order to learn how to behave or to be more prepared in real-life emergencies. The figures show the percentage of participants from each group, based on their replies. Summing up of the “Help me” and “Help me a lot” option for question #5 shows that 70% of the “Emergency SEE” group and 57% of the “Emergency SEE+SOLVE” group think it would be helpful, while only 43% of the “No emergency” group think that. The group “Emergency SEE” reported that VR would help them 25% more than the group “No emergency”. For question #6 these combined positive percentages are 53%, 66%, and 65% for “No emergency”, “Emergency SEE”, and “Emergency SEE+SOLVE”, respectively.

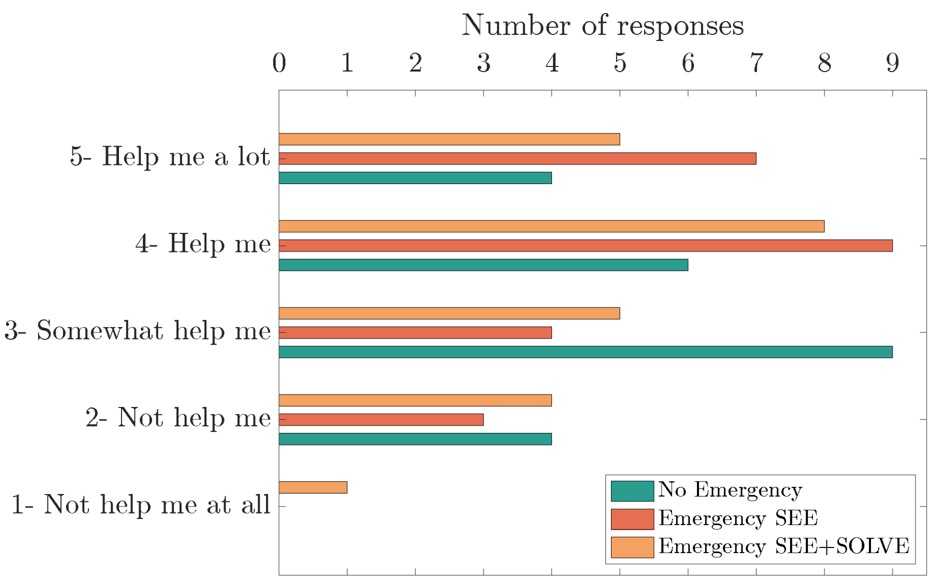

Figure 5. Distribution of the Likert scale scores per group. Question #5: How much do you think that having experienced an emergency in the virtual reality would help you being more prepared in the future for an emergency in the real plant?. a) No emergency, b) Emergency SEE, c) Emergency SEE+Solve. Participants: $n^{a)}$=23, $n^{b)}$=23, $n^{c)}$=23.

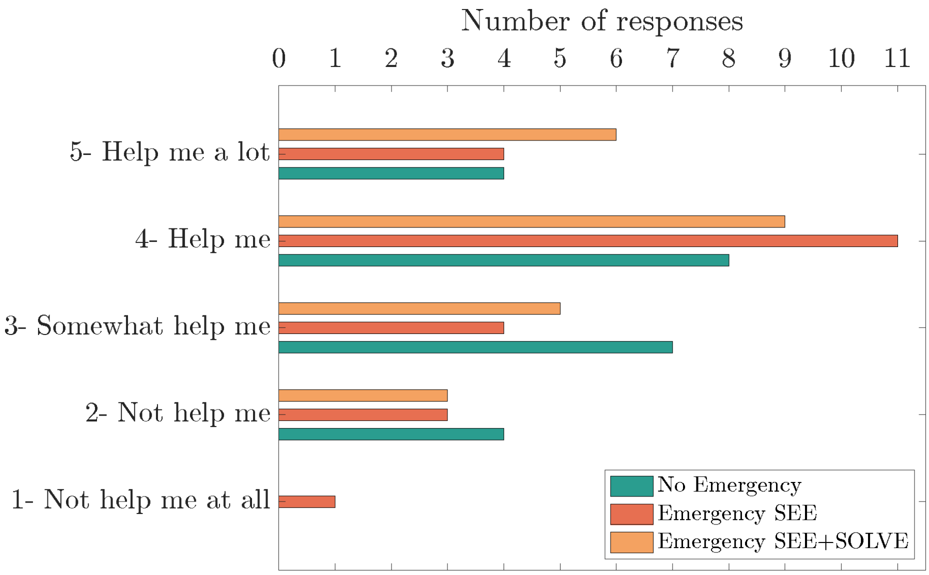

Figure 6. Distribution of the Likert scale scores per group. Question 6: How much do you think that having experienced an emergency in the virtual reality training would help you learn how to behave in a future emergency in the real plant?. a) No emergency, b) Emergency SEE, c) Emergency SEE+Solve. Participants: $n^{a)}$=23, $n^{b)}$=23, $n^{c)}$=23.

3.1.1. Examination of performance during emergency situation

Group "Emergency SEE+SOLVE" of experienced operators had the opportunity to solve emergency situation #2 "Loss of cooling", after seeing the consequences of emergency situation #1 "Dosing quantity reactant ClBu too high".

All the participants ($n^{SEE+SOLVE}$= 23) were able to solve the emergency situation in the time given (2.5 min). On average it took the participants 48.63 seconds (SD=34.53 sec) to solve the situation. 78% of the participants did not require any hints to solve the situation; three participants asked for two hints, which were hint #1 and hint #2; two participants asked to see the final hint that included the solution. As can be observed in Figure 7, the participants that required more hints were the ones that took longer to solve the situation.

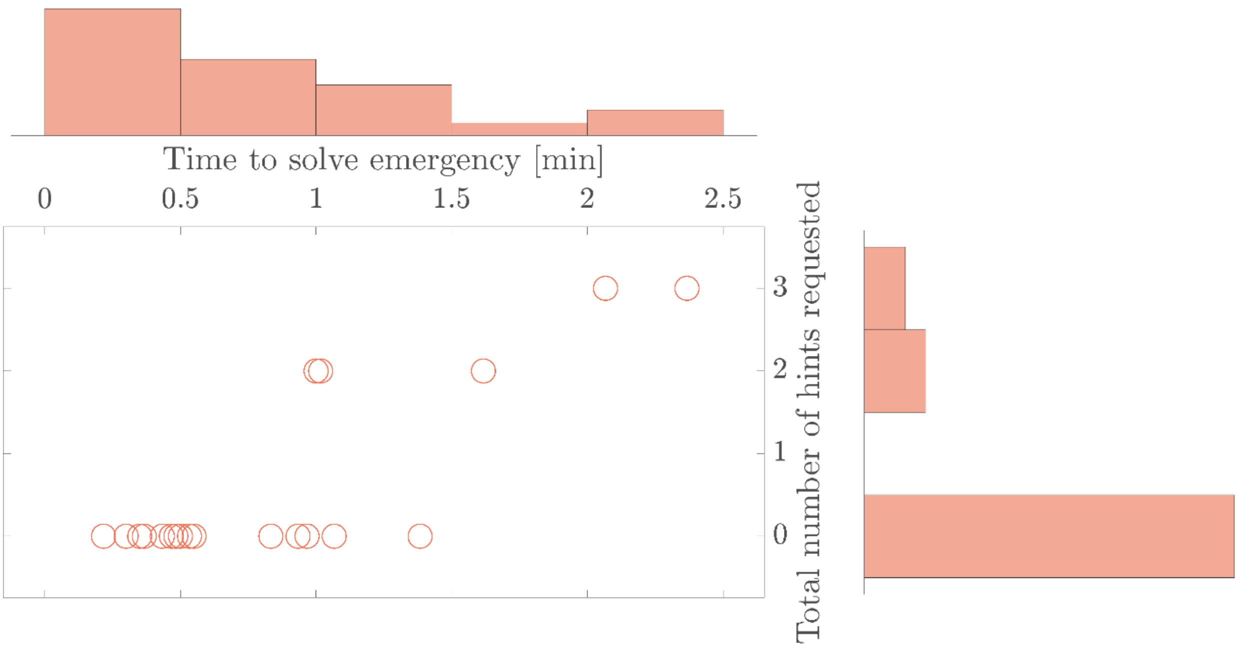

Figure 7. Time to solve emergency situation #2 vs the total number of hints requested by the participants (the horizontal histogram). The vertical histograms represents the distribution of participants (#) for each time duration. Participants: $n^{SEE+SOLVE}$= 23

Coincidently, one of the participants that took longer to solve the emergency, is the same participant that was an outlier in question #5. The second participant replied to both questions with a score of 4-Not help me, and wrote "I prefer real".

3.2. An investigation into operators' perspectives on VR emergency training

In addition to the Likert scale questions, the participants were asked: "Why did you choose this rating?". A variety of views were expressed. Data analysis reveals several recurring codes in the open answers (see Table 3). In some cases, multiple codes were identified in the response of one participant.

Table 3. Identified themes and codes for the open text replies to Questions 5 and 6.

Theme	Code (German)		Code (English)
	Kein Antwort, nicht relevant	A	No reply, not relevant
Positive	Gute Beispiel	B	Good example
	Ubung macht den Meister	C	Practice makes perfect
	Verbesserte Reaktion in real Leben	D	Improved reaction in real life
	Bessere lerneffekt durch sehen	E	Better learning effect when seeing/experiencing
	in der VR gibt es keine Gefahr	F	In VR there is not danger
	Realistisch	G	Realistic
	Immer wieder trainiert	H	Repeat again and again
	In Zukunft hilfreich sein	I	Potential for the future

	(Neue) Situationen üben	J	Practice (new) situations/tasks
Negative	Unvorhersehbare Reaktion in einem echten Notfall	K	Unexpected reaction in real emergencies
	Jeder Notfall ist anderes	L	Every emergency is different
	Realität ist anderes	M	The reality is something different
	Nicht richtig ausgereift	N	Not really mature yet

Unfortunately, it was observed when analysing both questions separately that the participants have not understood clearly the difference between the two questions: "being more prepared" / "learn how to behave". For example, one participant said in response to question #5: "On-site conditions are very different from the virtual "world"". While another participant replied to question #6: "reality is always something else". The codes identified in both questions are quite similar. Table 3 shows the codes found in the replies to each question. In addition, for question #6 several participants copy-pasted the replies from the previous question, giving another indication that they did not comprehend the difference between the questions. The duplicate replies were not considered as a new code.

Two types of themes were identified in the responses of the participants: positive and negative. As a general overview, excluding the "no response" items, 71% and 80% of the participants reported positive themes for questions #5 and #6, respectively. These values provide an indication that most of the participants felt that training emergency situations in virtual reality could be useful and help them, which was also observed in the positive Likert-scale results.

Figure 8 presents the distribution of answers, coded for the three groups of participants for question #5. In the figure, the legend is the same for all groups, and the number of participants that have referred to each code is presented in the pie chart.

Some participants opted not to provide a written reply, or the response was not relevant to the questions (e.g. "Headache"). For question #5 these represent 34.7%, 17% and 26% for the "No Emergency", "Emergency SEE", and "Emergency SEE+SOLVE" groups, respectively. As mentioned before for question #6 these percentages were higher: 69.6% for both first groups and, 47.8% for the last one.

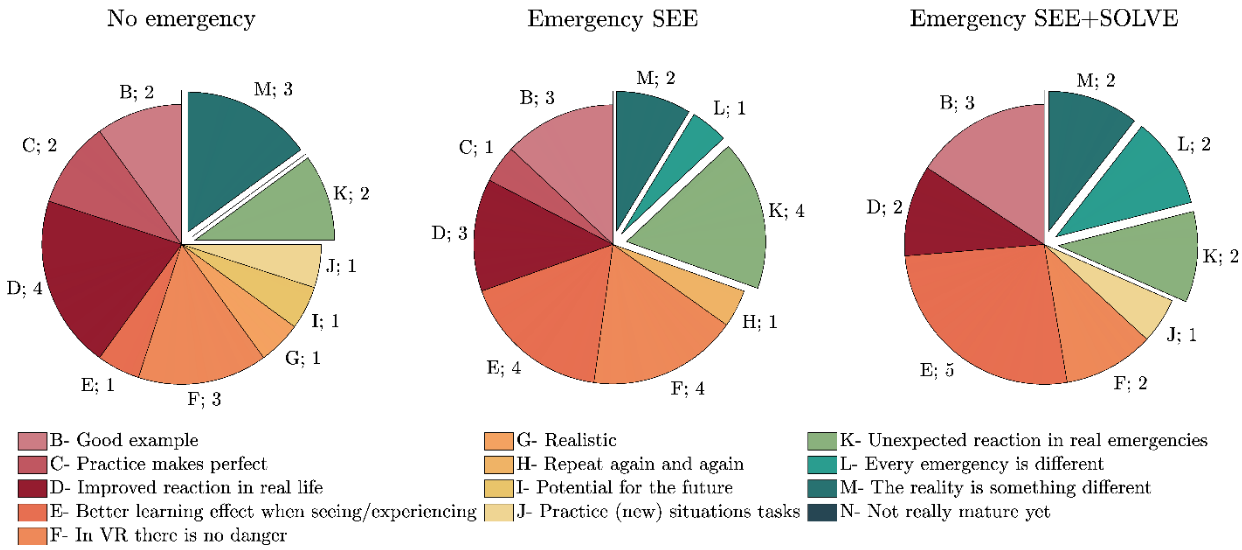

Figure 8. Pie chart of codes for Question 5 per group. The number of participants that mentioned each code is presented in the plot, as several participants mentioned more than one code the total number is higher than the number of participants per group. Code A (No reply, not relevant) is not included $n^A_{No\ Emergency}$=8, n^A_{SEE}=4, $n^A_{SEE+SOLVE}$=6. In explode mode is the negative theme highlighted, including codes K, L, M and N.

For question #6 (Figure 9), the group “no emergency” is the one that mentions the fewest number of distinct codes, with only five of the codes present in their replies B, C, D, J, N. Another observation is that group “Emergency SEE+SOLVE”, mentioned “J- Practice (new) situations/tasks” several times, in comparison to the other two groups.

Looking at the number of responses for both questions together (Figure 8 and Figure 9), it can be observed that the code “D- Improved reaction in real life”, was mentioned by 12 participants in total. It was mentioned by the “no emergency” group more frequently than by both the other groups. This is a rather unexpected result, as it presents some indication that the participants that did not see the emergency think it would improve their reaction, but the participants that actually saw and experienced emergencies do not think this as much.

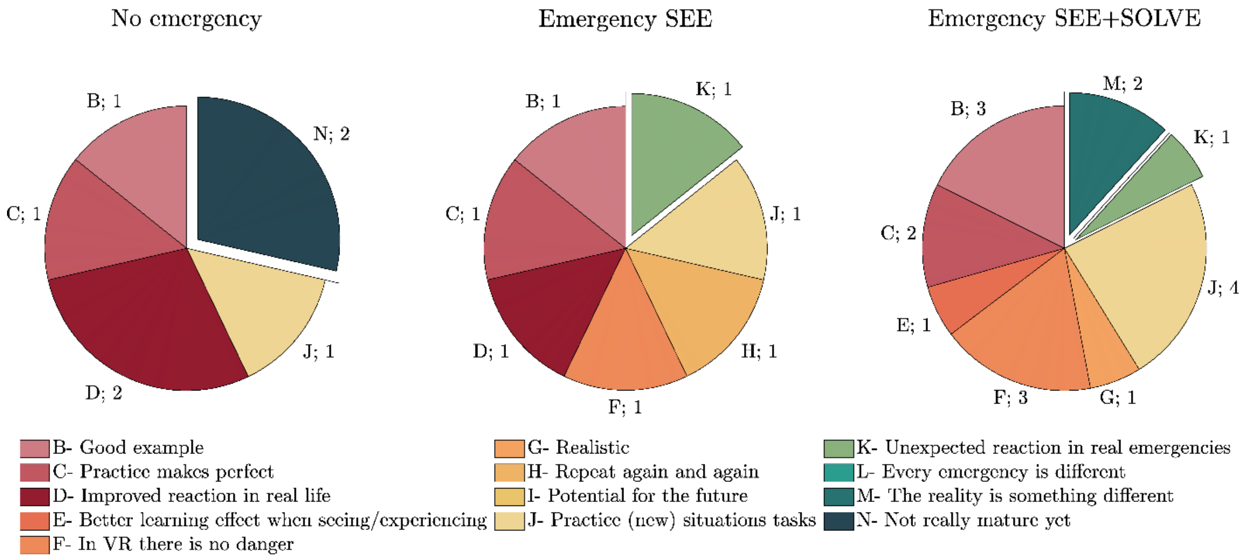

Figure 9. Codes for Question #6 per group. The number of participants that mentioned each code is presented in the plot, as several participants mentioned more than one code the total number is higher than the number of participants per group. Code A (No reply, not relevant) is not included $n^{A}_{No\ Emergency}$=16, n^{A}_{SEE}=16, $n^{A}_{SEE+SOLVE}$=7. In explode mode is the negative theme highlighted, including codes K, L, M and N.

The code “E- Better learning effect when seeing/experiencing”, was reported by five more participants in the group “SEE+SOLVE”, and three from “SEE”. This might indicate a tendency that participants that saw an emergency (in this VR version it was the explosion of the reactor), think it will have a better learning effect; but the participants that only had to imagine an emergency in VR, do not identify this potential as much.

The code “F- In VR there is no danger” is also interesting to highlight, as more participants from groups “SEE” and “SEE+SOLVE” reported it in comparison with “no emergency”. Even though the explosion of the reactor in VR is not photorealistic, it is quite impressive to see in VR as no one can see and experience this in real life. And the participants noted it correctly, in VR there is no danger. They can train and learn in a practical safe environment, knowing that they can make mistakes without consequences and learn from them.

Next, it is observed that in the group “SEE+SOLVE” three more participants reported the code “J- Practice (new) situations/tasks”. This is an interesting and rather expected outcome. It shows that the only group that was able to solve an emergency, is the one reporting that VR is allowing them to practice new situations. According to these data, it may be possible that the participants of the other two groups did not think of that when imagining what it would be like to be able to practice and solve an emergency in VR.

Finally, the code “K- Unexpected reaction in real emergencies”, is mentioned more frequently by the participants that experienced the emergency. This indicates that seeing the emergency, made the participants reflect on the fact that after that they would not know how they would react in real life.

As a final analysis, a deeper look at the written replies of the participants of the three groups was conducted, while questions #5 and #6 are examined together. This is why the reported percentages do not add up to 100, as the percentage refers to the number of participants from the three groups (total of 69 participants) that reported that item. In Figure 10 a cross-reference of the codes and the Likert scale is presented. The description of the codes per topic is presented below, together with examples of the participant's views (Group “No emergency”=G4, Group “SEE”=G5, Group “SEE+SOLVE”=G6).

One participant from the group “SEE” reflected exactly as it was intended: “… I often ask myself what it would be like in an emergency? How would I react? Would I not know what to do because of panic?...”. This participant also reflected on the fact that they are only told what to do theoretically and there is no room for practical training; but if VR would allow for this, it should be used, as it can “prevent something worse”. Another participant reported that even though the VR was not exactly the same as the real plant, the actions and response in an emergency can be “very well integrated into the daily work”.

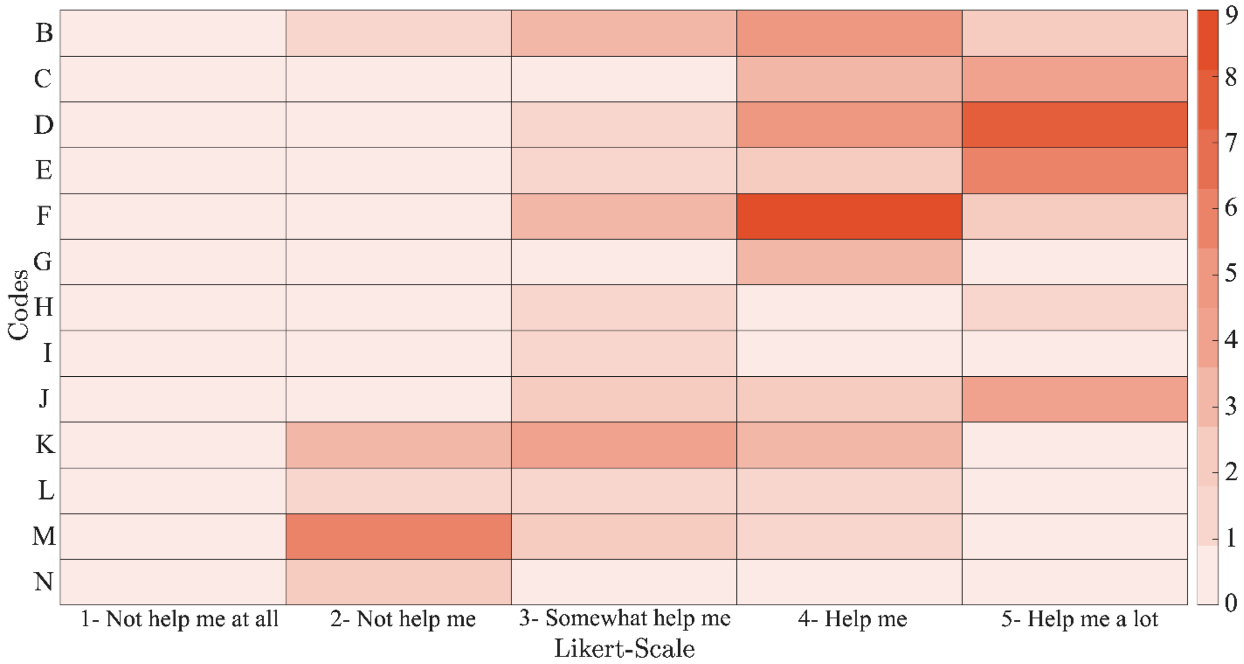

Figure 10. Cross-reference of codes presented in the open-text replies vs. the Likert-scale score of the participants. Question #5 and #6 were added, and the code "A-No reply, no relevant" was not included. Positive codes: B- Good practice, C- Practice makes perfect, D- Improved reaction in real life, E- Better learning effect when seeing Experiencing, F- In VR there is no danger, G- Realistic, H- Repeat again and again, I- Potential for the future, J- Practice (new) situations tasks; Negative codes: K- Unexpected reaction in real emergencies, L- Every emergency is different, M- The reality is something different, N- Not really mature yet. The colour coding reflects the number of participants using the given response/code.

Nineteen percent of all the participants indicated that one benefit of training in VR is that there is no real danger (F- In VR there is no danger). They referred to the fact that they could stay calm during the training because they knew that the danger was not real. In addition, they mentioned several times that they can make and see the mistakes, and observe how the situation evolves, trying different approaches, all from the safety of VR. The participants that mentioned this code were the ones that also chose the score "5- Help me a lot" on the Likert scale most frequently.

G4: " … in VR you could stay calm in case of mistakes because they are not real…"

G4: " … it is not so dangerous…"

G5: " … you can see when mistakes are made…"

G5: " … Behavioral patterns can be trained … In a safe environment…"

G6: " … [VR] is simply safer"

To assess the "self-perception" of the participants two main aspects were evaluated: how much emergencies in virtual reality helped the participant being more prepared and learn how to behave in a future emergency in the real plant. These two topics were mentioned across the replies, with positive (+) and negative (-) themes.

<u>Learn how to behave</u>

- **C- Practice makes perfect (+).** 10% of all the participants replied that practising is always useful, would help you being more prepared, and having the possibility of repeating training would "make perfect". Those participants replied with "4- Help me" and "5- Help me a lot" on the Likert scale.

  G4: "… practice always helps to be prepared…"

  G5: "… it is always better to train beforehand to learn and prepare for emergencies…"

  G5: "… practice makes perfect…"

  G6: "… practice makes you more experienced…"

- **D- Improved reaction in real life (+).** 17% of all the participants mentioned that practising in VR would improve the reaction in real life in case of an emergency. Those participants mostly replied with "4- Help me" and "5- Help me a lot" on the Likert scale. Examples presented below display the type of improvement that the participants think they would see in their reaction: cool head, more prudently, faster, better. This directly relates to learning how to behave, they reported that practising actions and procedures would allow them to know what to do and keep calm in case of an emergency.

  G5: "… you can react more prudently…"

  G5: "… act faster in real life…"

  G6: "… can help to keep a cool head on-site…"

  G6: "… might help you to keep a cool head and react correctly…"

- **K- Unexpected reaction in real emergencies (-).** 14% of all the participants reported an opposite opinion. They think that even though you can train an emergency in VR, and practice procedures and how to react, being in an emergency in real life is something different and no one would know how anyone would react. These participants think it would not be possible to learn how to behave. However, their replies to the Likert scale were distributed between "2-Not help me" and "4-Help me", with a peak in "3- Somewhat help me".

G4: "… only in an emergency, you know how you react…"

G4: "… how one reacts in reality to the same previously simulated mistakes is, of course, unpredictable"

G5: "… people in distress always react differently, it is difficult to learn the right behaviour…"

G5: "… in a real case of danger, you would behave very differently than in the virtual world. Here you know that nothing can happen to you…"

G6: "… you cannot train how to really behave in an "emergency"…"

G6: "… you never know how you will react…"

<u>Being more prepared</u>

- **E- Better learning effect when seeing/experiencing (+).** 16% of all the participants indicated that their learning would improve if they were able to see or experience the -in this case- emergency, rather than listening to the content in a classroom. Mostly those participants also rated "5- help me a lot" on the Likert scale. They reported that VR is improving learning, then indirectly it can be extrapolated that VR is helping to being more prepared.

G5: "… when you see something, you learn better from it…"

G6: "… experiencing emergencies virtually is better than … only being told about them…"

G6: "… a visual emergency is more memorable because you can see what is happening …"

- **L- Every emergency is different (-).** 4% of all the participants reported that even though they could train an emergency in VR, it would not help much because every emergency is different. As mentioned before, this can be linked to the fact that in the VR simulation only one example was provided to the participants, and they replied with their opinion based on this one example of an emergency. It is, of course, a fact that every situation would start and evolve differently.

G6: “… rehearsing emergencies is very difficult because they are usually very individual problems”

G6: “… every emergency situation is different…”

M- The reality is something different (-). 13% of all the participants make specific mention of the fact that the VR simulation was not realistic enough. This of course makes sense since the VR was not designed to be photorealistic, or to include features such as noises of valves (it did include alarms) or vibrations. This code is the one that received the most negative score on the Likert scale: most participants replied mostly “2- Not help me”.

G4: “cannot be compared 1:1 with reality”

G4: “… it is not the same as a real emergency situation…”

G5: “a real boiler explosion is more frightening to watch than a virtual one”

G5: “…compared to reality the feeling is missing. Noise, vibrations, heat, other environmental factors influence people…”

G6: “on-site conditions are very different from the virtual world”

G6: “…in the reality, it is always different…”

4. Discussion

The results of this research showed that no statistically significant difference was found in the median of Likert scale responses among the three groups: “No emergency”, “Emergency SEE”, “Emergency SEE+SOLVE”. These findings suggest that in general, regardless of the VR experience (e.g. emergency, no emergency), the participants found having emergency situations in VR as a useful tool for their training. These results are consistent with the qualitative analysis of the written replies of the participants, in which approximately 75% of the reported codes were positive. For the positive codes, it was mentioned that practising in VR allows participants to safely make mistakes, see the consequences, and repeat the procedure as many times as needed, because “practice makes perfect”. They also consider that their learning would improve with the possibility of seeing and experiencing emergency situations.

In addition, the participants reported that their reaction in real-life emergencies would improve, as they would be able to stay calmer, think faster, and react correctly and more prudently. However, other participants contradicted this mentioning that the training of emergencies in VR would not help them behave better in a real-life emergency, because the reaction of people under stressful conditions would be unexpected. Of course, the process of decision-making in an emergency is different to the one in normal and daily conditions [12]. However, the reaction in emergency situations can be trained and operators can (and must) learn how to act in case of unexpected circumstances [13]. Some reported that there the expectation of panic behaviour in case of emergencies is a misconception . For example, in case of fires the people's escape behaviour is “much more predictable than is commonly assumed” [14,15]. Moreover, repetition can be the key to adapt an expected behaviour, helping the learner being more prepared can being able to keep calm in an emergency. This is particularly true, when we consider Kerin’s [16] analysis of the Naturalistic Decision Making introduced by Klein and Zsambok [17], emphasizing the need for exposing decision-makers to opportunities for consequence assessment based on the ‘recognition of the signals or patterns which they are seeing’. Hence seeing both the signs of an emergency as well as the consequences in a realistic, yet safe, setting contributes to more secure embedding of appropriate decision making. Kerin [16] also highlighted the importance of learner engagement in this process. Whilst the publication is already 15 years old and discusses interactive websites and animations as effective means of engagement, developments in education technology and the introduction of VR clearly enhances potential learner engagement, increasing the chances of more effective learning [18,19].

Additionally, the IChemE Safety Centre (ISC) differentiates knowledge from competence: “Competency is a combination of practical and thinking skills, experience and knowledge” [20]. Operators should be able to demonstrate defined behaviours, which would be the outcome of training “both off-the-job and on-the-job”. However, from a research point of view, it is complicated and challenging to study and verify the behaviour responses under real emergency conditions, for “ethical and safety reasons” [21].

Other participants refer to the lack of realism as a negative aspect of emergency training in VR. This was also reported participants of Saghafian *et al.* [22] study of VR fire extinguisher training. In their qualitative analysis comments showed that lack of realism was a concern. Understandably, less fear and stress would be transmitted in VR, but arguably this should be considered a positive aspect: if the participants can train calmly, they would be able to learn and internalize the information better. Nevertheless, multisensory VR (such as visual, auditory, thermal and olfactory) could supplement those experiences. For example, results of the report on “Multi-sensory virtual environments for health and safety training” of the Institution of Occupational Safety and Health (IOSH) suggest that participants that experienced multi-sensory stimulus “felt a greater sense of urgency in response to the fire” [21]. In contrast, it has been reported that focus of the training should be on the purpose of the content rather than the exact replication of reality [23,22]. Further research should be conducted to assess the impact of photorealistic VR experiences on the perception of the operators training emergency situations, and the benefit of the extra effort in the VR development.

Finally, the thematic analysis conducted in this study was performed only by one researcher. Future research should contemplate including a second independent coder, to guarantee intercoder reliability of the qualitative analysis.

5. Conclusions

The current study assessed the self-perception of the participants on safety readiness when exposed to emergency situations in virtual reality, and evaluated if the responses would differ if different emergency situations were presented to the participants.

The data analysed included Likert scale and written open-ended responses from 69 participants from Germany. It was found that the exposure route of emergency (e.g. emergency, no emergency), did not impact in the participants responses. Results need to be interpreted with caution, due to the low number mentions in each code reported in the open-ended questions.

Taken together, the results indicate that the operators believe emergency training would them to better learn and be more prepared in case of a real-life emergency. Even though virtual reality is, so far, something different from reality, it should be considered as a tool to help the operators trained and learn the procedures that are impossible to train in real life.

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6. References

[1] Nakai, A. Scenario Development for Safety Training/Education System in Chemical Plant. *Science Journal of Education 3*, 3 (2015), 68.

[2] Gallegos-Nieto, E., Medellín-Castillo, H. I., González-Badillo, G., Lim, T., and Ritchie, J. The analysis and evaluation of the influence of haptic-enabled virtual assembly training on real assembly performance. *International Journal of Advanced Manufacturing Technology 89*, 1-4 (2017), 581–598.

[3] Mól, A. C. A., Jorge, C. A. F., Couto, P. M., Augusto, S. C., Cunha, G. G., and Landau, L. Virtual environments simulation for dose assessment in nuclear plants. *Progress in Nuclear Energy 51*, 2 (2009), 382–387.

[4] Kluge, A., Nazir, S., and Manca, D. Advanced Applications in Process Control and Training Needs of Field and Control Room Operators. *IIE Transactions on Occupational Ergonomics and Human Factors 2*, 3-4 (2014), 121–136.

[5] Soós, R., Balogh, B., Dobos, G., Szávai, S., and Dudra, J. Innovative technologies in training and education for maintenance team of NPPs. *EPJ Nuclear Sciences & Technologies 5*, December (2019), 21.

[6] Srinivasan, B., Iqbal, U., Shahab, M. A., and Srinivasan, R. Review of virtual reality (vr) applications to enhance chemical safety: From students to plant operators. *ACS Chemical Health & Safety* (2022).

[7]Kletz, T. An engineer's view of human error. *An Engineer's View of Human Error, Third Edition* (may 2018).

[8] Kruskal, W. H., and Wallis, W. A. Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association 47*, 260 (1952), 583–621.

[9] Dodge, Y. Kruskal-wallis test. *The Concise Encyclopedia of Statistics*(2 2008), 288–290.

[10] Guest, G., MacQueen, K., and Namey, E. Applied thematic analysis. *SAGE Publications, Inc.* (12 2012).

[11] Nowell, L. S., Norris, J. M., White, D. E., and Moules, N. J. Thematic analysis: Striving to meet the trustworthiness criteria. *SAGE Publications 16* (10 2017).

[12] Fahy, R. F., Proulx, G., and Aiman, L. 'PANIC' AND HUMAN BEHAVIOUR IN FIRE. In *4th International Symposium on Human Behaviour in Fire* (2009), pp. 387–398.

[13] Kletz, T. An engineer's view of human error. *An Engineer's View of Human Error, Third Edition* (may 2018).
[14] Sime, J. *Escape behaviour in fires: Panic or affiliation. - University of Surrey*. PhD thesis, University of Surrey, 1984.
[15] Sime, J. D. The concept of panic. *Fires and human behaviour 1*, 5 (1980).
[16] Kerin, T. Learning from incidents: A practical application. *Process Safety Progress* 28, 1 (2009)
[17] Klein, G., and Zsambok, C. Naturalistic Decision Making, *Lawrence Erlbaum*, USA, 1996.
[18] Udeozor, C., Russo-Abegão, F., Glassey, J. Perceptions and factors affecting the adoption of digital games for engineering education: a mixed-method research*. International Journal of Educational Technology in Higher Education 20:2 (2023)*
[19] Chan, P., Van Gerven, T., Dubois, JL., Bernaerts, K. Study of motivation and engagement for chemical laboratory safety training with VR serious game. *Safety Science* 167 (2023)
[20] ISC. Isc process safety competency guidance. https://www.icheme.org/media/9391/supplementary-guide-march-2019.pdf. 2018.
[21] Lawson, G., Shaw, E., Roper, T., Nilsson, T., Bajorunaite, L., and Batool, A. Multi-sensory virtual environments for health and safety training. Tech. rep.
[22] Saghafian, M., Laumann, K., Akhtar, R. S., and Skogstad, M. R. The evaluation of virtual reality fire extinguisher training. *Frontiers in psychology 11* (11 2020).
[23] Salas, E., Tannenbaum, S. I., Kraiger, K., and Smith-Jentsch, K. A. The science of training and development in organizations: What matters in practice. *Psychological Science in the Public Interest, Supplement 13* (6 2012), 74–101.
[24] Garcia Fracaro, S., Chan, P., Gallagher, T., Tehreem, Y., Toyoda, R., Bernaerts, K., Glassey, J., Pfeiffer, T., Slof, B., Wachsmuth, S., and Wilk, M. Towards Design Guidelines for Virtual Reality Training for the Chemical Industry. *Education for Chemical Engineers* (2021), Under Review.
[25] Garcia Fracaro, S., Glassey, J., Bernaerts, K., and Wilk, M. Immersive technologies for the training of operators in the process industry: A Systematic Literature Review. *Computers and Chemical Engineering 160* (2022), 107691.