HCI Issues, Design and Development for a First Responders VR Training System on Dangerous Goods Transportation Incidents

Bruno Emond(✉), Jean-François Lapointe, Max Kinateder, Eric DeMarbre, Maxine Berthiaume, Irina Kondratova, Natalia Cooper, Noureddine Bénichou, and Stephen Downes

National Research Council Canada, Ottawa, Canada
{bruno.emond,jean-francois.lapointe,max.kinateder,eric.demarbre,
maxine.berthiaume,irina.kondratova,natalia.cooper,noureddine.benichou,
stephen.downes}@nrc-cnrc.gc.ca
https://nrc-cnrc.canada.ca

Abstract. This paper reports on our progress in the development of a virtual reality (VR) training environment where novice first responders in remote areas are acquiring situational awareness and procedural knowledge for the management of dangerous goods transportation incidents. Our research and development efforts aim to address the problem of providing engaging, realistic, safe, and cost-effective means to train first responders. The adopted process includes conducting requirements analysis in partnership with key stakeholders, as well as the design, development and empirical evaluation of the VR system with sufficient autonomy to support multiple use cases, realistic scenario variations, and real-time feedback during scenario execution.

Keywords: Virtual reality · Dangerous goods incidents training · First responders · Adaptive instructions

1 Introduction

This paper reports on our progress in the development of a virtual reality (VR) training environment where novice first responders are acquiring situational awareness and procedural knowledge for the management of dangerous goods transportation incidents [4]. The system is being developed with off-the-shelf components including commercial untethered Head Mounted Displays (HMD) and widely used cross-platform game engine. Scene 3D models and scripts are added to the off-the-shelf software to provide a realistic training environment and adaptive instructions to allow learning by doing in a self-paced manner.

The paper contains seven sections: problem statement, requirements analysis in partnership with stakeholders, human-computer interaction (HCI) issues, system design, evaluation plan, and summary and conclusions. The problem statement outlines some of the problems/issues the training system is addressing. The

P. Zaphiris and A. Ioannou (Eds.): HCII 2022, LNCS 13329, pp. 48–60, 2022.
https://doi.org/10.1007/978-3-031-05675-8_5

requirements section briefly describes how the development team has partnered with subject matter experts and stakeholders to determine key requirements. The HCI issues section presents current challenges faced during the development of the VR training environment, followed by a section on design solutions to overcome issues. An evaluation plan section presents the empirical methods put in place for characterizing learning processes and evaluating the effectiveness of the training environment. The paper concludes with a discussion of the next steps in the system development and evaluation.

2 Problem Statement

Fire emergencies affecting transportation of dangerous goods in remote areas are low-probability but high-consequence events. Training first responders to manage such incidents poses unique challenges given that training resources are often limited (both in budget and time), on-the-job training is unlikely to happen, and safely simulating high-impact training scenarios in the real world is next to impossible. Conventional training methods for dangerous goods incidents for first responders are also limited in terms how engaging, realistic, safe, and costly they are [5,8,10]. Furthermore, the training expertise is often located in urban areas, whereas trainees may be located in remote areas. This suggests that a technology-based approach could offer an essential element to increase first responders' awareness, operation, including procedural knowledge and skills.

Previous research literature points to the a lack of studies assessing training and knowledge gaps of first responders with regards to on-scene decision making, including problems with response tactics, improper assessment and handling of suspicious material, and improper use of personal protective equipment [6]. Our research and development (R&D) efforts aim to address the problem of providing engaging, realistic, safe, and cost-effective means to train first responders in remote areas on the management of dangerous goods incidents. This process includes conducting a requirements analysis in partnership with key stakeholders, as well as the design, development and empirical evaluation of a VR system that has sufficient autonomy to support multiple use cases, realistic scenario variations, and real-time feedback during scenario execution. VR offers a potential alternative to live training methods or web-based e-learning solutions, allowing for realistic and safe simulation of a wide range of dangerous goods incident scenarios. VR training allows the implementation of behavioural training with real-time feedback in complex multi-user simulations. When deployed at scale, VR training quickly becomes more cost-efficient than comparable training alternatives (e.g., physical training) [5,11]. In addition, the effectiveness, credibility and validity of VR training needs to be assessed and compared to existing training methods.

3 Requirements Analysis with Stakeholders

A technical advisory group (TAG) of subject matter experts was established to provide timely information and feedback to ensure that the VR training proof of concept meets the stakeholders' needs and their experience. The information and feedback are obtained through regular meetings and back and forth discussions with the TAG, which led to defining the major requirements. The requirement analysis has enabled to identify a set of specifications related to the context of use, training objectives, and scenario configurations. Requirements were based on the problem description, recommendations from the TAG members, and relevant emergency response guides.

3.1 Technical Advisory Group

A technical advisory group of subject matter experts was established to provide timely information and feedback to ensure that the VR training proof of concept meets the stakeholders' needs. Membership in the TAG team was done by invitation with participants selected to ensure a broad geographical representation and direct experience with emergencies affecting transportation of dangerous goods in remote areas. The TAG included members from the Canadian Association of Fire Chiefs, the Canadian Transport Emergency Centre operated by the Transportation of Dangerous Goods (TDG) Directorate of Transport Canada, a community fire and emergency services, a community hazardous materials section, a provincial firefighter school, a provincial fire Marshall, and the National Fire Protection Association. Project members served as observers but did not participate in the group decisions.

TAG members provided information and expert advice on the training needed by first responders who may be exposed to the threat of fires from the transportation of dangerous goods. Topics examined included scientific, environmental, health, and safety issues. Members were asked to provide comments on the overall research work, comments on a survey to be submitted to stakeholders, input to the development and assessment of the VR tool, and input to help answer any unresolved issues that may arise during the project. The main research team met with TAG members four times by videoconference over the first year of the project. The main efforts were focused on clarifying the training objectives, identifying authoritative legislation, manuals and guides, and offer general comments on iterative versions of the VR scenario as it was being developed.

3.2 Context of Use

Through consultation with domain experts, the following requirements were identified regarding the context of use.

1. Given that the target user group is potentially located in areas without broadly available internet, a training tool needs to have relatively autonomous (offline) processing capabilities. This means that a standalone application for learning and skill maintenance is needed;
2. Given the wide range of potential scenarios and associated required skill levels, a flexible software development paradigm (flexibility in scenario design, in deployment of measurements, assessments, and tutoring strategies) is needed.

This also requires identification of key software elements to capture learners' behaviour and performance;
3. Given that training may also occur supervised, in both, group or individual sessions, capabilities for group usage and/or screencasting are required.

3.3 Training Objectives

First responders can generally be grouped into three skill level categories (with increasing levels of competencies and responsibilities): Awareness level, Operations level, and Incident Command level [15]. The proof of concept VR training tool described in this paper will target trainees at the *Awareness Level* category. First responders who are trained and certified to the Awareness level are individuals who may be the first to arrive at or witness a hazardous material or chemicals incident. They are expected to assume certain responsibilities when faced with an incident involving hazardous material. These responsibilities can be associated with high-level training objectives and include these main steps:

1. Recognize and identify hazardous materials;
2. Protect themselves and others from hazards;
3. Isolate the hazard area and deny entry;
4. Communicate information to an appropriate authority and calls for appropriate assistance.

In addition to the advice from the technical advisory group (TAG) of experts, the Emergency Response Guide [15], NFPA 470: Hazardous Materials/Weapons of Mass Destruction (WMD) Standard for Responders [13], and Transport Canada Competency guidelines [16] were used to identified training requirements.

The main training objectives for the first version of the VR training tool focuses on a first responder being able to safely gather and communicate information about the observed incident. The training objectives do not include actions needed to secure and isolate the hazard area. The following specific learning goals were defined:

1. Approach and safe positioning: This requires the trainee to "not rush in", and recognize information provided by the environment. To safely approach the scene, a responder should seek an upwind and uphill position to start investigation and stay at a safe distance from the hazardous materials location (i.e., outside the initial isolation distance);
2. Hazard identification: This requires using provided inventory tools (e.g., binoculars, a copy of the Emergency Response Guidebook (ERG) [15]) to retrieve information from, for example, placards attached to the transporter (e.g., UN number), and then to recognize associated hazards;
3. Situation assessment and communication: A responder needs to communicate the incident to emergency services and, if needed, to Canadian Transport Emergency Centre (CANUTEC). In this step, the trainee is able to use a cellphone which is provided as inventory tool in VR environment.

3.4 Scenario Configuration

Based on the context of use and training objectives and following the TAG advice and input, a simple proof of concept scenario was developed, in which a trainee would need to diagnose a hazardous material incident and communicate their findings (note that isolating the scene/denying entry was not included in the training goals defined for this scenario).

The scenario is intended to be a relatively simple and relatively common occurrence. The trainee is faced with the following scenario:

- A truck with a cabin and a trailer is jackknifed close to a road;
- The truck is transporting an (initially) unknown (potentially) hazardous material;
- It is unclear whether any or how much material has spilled;
- There are no obvious signs of fire (e.g., smoke);
- There are no buildings or people in the immediate vicinity of the incident;
- It is daytime and overall visibility is good;
- The environment contains vegetation on the side of the road, a small river/brook/ and there is a point of elevation not too far away;
- Continuous wind from one direction;
- Daytime temperatures are below 30C and above 0C;
- No dynamic changes in the scenario (i.e., no fire development, no change in wind direction, etc.).

4 HCI Issues

In order to support training and performance in the VR environment it is necessary to provide appropriate, task relevant cues that can be represented as design features in the simulation. The presence of these instructional design feature within the simulation is important not only for initial training but also for training transfer. Some of the examples of this feature include on screen feedback during simulation or additional sensory cuing in VR. Even though some of these features can reduce the overall fidelity of the simulation, research has shown that the informational content of these features, even if they disrupt fidelity, can enhances not only performance but also overall user experience in virtual environments [2,3].

When considering the elements that must be simulated in a virtual environment to provide an adequate level of training efficiency, several issues emerged. For example, browsing and reading a book in VR, by using solely an HMD and hand controllers is a different experience than in real life (IRL). Other aspects, such as simulating wind, smell and heat using only audio-visual displays technologies asks for some creativity in order to communicate this information in a way that makes sense to users without the possibility of simulating them by using other communication channels. The sections below describe in more details which HCI issues were encountered and subsequently addressed during software development.

4.1 User Boundaries

A VR technology that is proposed to be used in this study is the Oculus head-mounted display. All Oculus VR systems first require to determine the user boundaries, i.e., whether the user will be able to walk in the whole room (a.k.a. room scale boundary) to indicate a safe place to move whilst using VR headset, as well as determine standing or sitting boundary (stationary boundary). These boundaries serve as guidance for the user and they appear when the user approaches too close to boundary edges as a user warning of the possible unsafe actions. In this study, sitting stationary boundary is chosen for the testing to protect novice users of possible injuries that could be caused by falls on the ground as well as reduce possible discomfort (motion sickness) that the user might experience during the movement in VR environment.

4.2 Available Input Devices

In our proposed VR set-up, the hand controllers with ray casting can be used to select, deselect, move or turn the objects or used them to re-locate oneself within the VR environment. The user can also change the position of the head whilst wearing the headset to enable some additional locomotion. The only way to act in the VR environment is by either using the hand controllers or by changing the pose of the head with the headset on. Gesture and speech recognition have been turned off because of interference with the hand controllers and noise in the environment, as well as their limited options in terms of tasks input.

4.3 Locomotion

Locomotion is the motor component of the navigation (which also integrates wayfinding) that allows for virtual walkthroughs in the scene. These walkthroughs are enabled by using the thumb stick located on the left-hand controller combined with the orientation of the headset (which indicates the direction of fore/aft axis). This allows for 3°C of freedom, namely fore/aft and sideways (left thumb stick), as well as the rotation of the head according to the vertical axis.

4.4 Gaze

Since we use a sitting stationary boundary, the viewpoint of the user is controlled mainly by the orientation of the head (pan/tilt/roll) with a quasi-fixed location in space.

4.5 Menu Selection

Selecting items on the menus presented by the headset is done by a vector-based pointing technique called ray-casting in the 3D space [12]. Each hand controllers cast such a ray and menu selection is done by pointing at it with one of the rays and by pulling the trigger of the hand controller related to that ray. Ray-casting selection is used both to start the application and to select the scenario to be used in the application itself. Ray-casting selection is illustrated in Fig. 1 below.

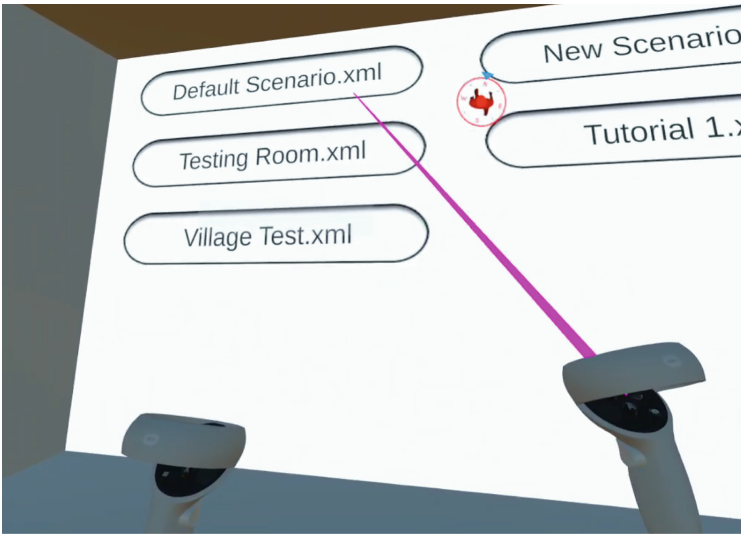


Fig. 1. Ray-casting menu selection of the scenario

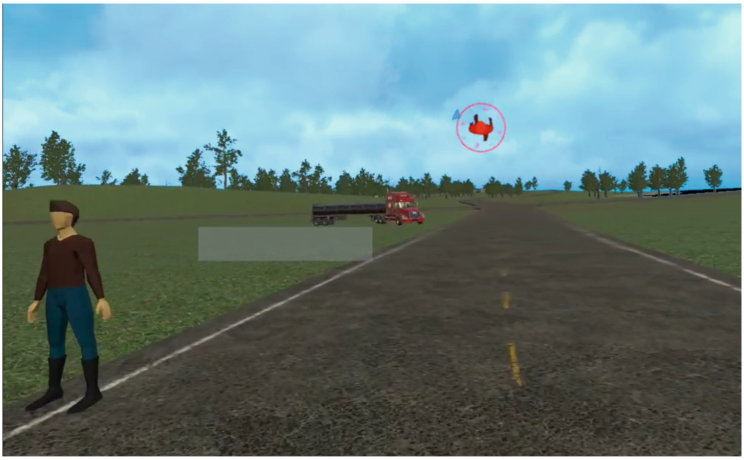


Fig. 2. Illustration of the dangerous good transportation incident scene. Compass (red circle) indicates user's orientation and the wind direction is indicated by a small blue triangle.

4.6 Wind Simulation

Given that our user interface is only audio-visual and contains no somatic display, we relied on the use of a visual icon of a compass to illustrate both orientation in space and wind direction. This compass (in red) is illustrated in Fig. 2. It shows the silhouette of a person viewed from above (orientation in space), coupled with a cursor that indicates wind direction.

4.7 Dialogue Interaction

In a 3D desktop application, during a dialogue interaction, the system can halt all movement and require the user to interact with the dialogue before returning to the simulation. This process does not work in a VR environment since stopping head movement whilst immersed in a virtual environment could give rise to some undesirable effects, including motion sickness or disorientation. When in VR environment, user's eyes and head will track towards the interface element they want to select. If the user interface element is attached to the head movement, the element is able to move in space. At the same time, the user simultaneously tries to follow with the controller's ray casting, creating a situation where the pointing line will be chasing the user interface element. The solution to this issue consisted of halting the player's lateral movement but leaving all rotational movements associated with the head active. A dialogue interface fixed in space would then appear in front of the user's current forward-facing direction so that they could interact with it while still looking around. Once the dialogue is ended, the system restores lateral movements.

4.8 Heat and Smell Simulation

Given similar constraints as for wind simulation, i.e., no somatic or olfactory displays, we used simple text messages in a floating dialog box to indicate the detection of heat or smells by the avatar in the VR simulation.

4.9 Inventory Management

In order to complete a task correctly, the learner has to use several tools that are available to them in the inventory. The inventory includes following tools: the Emergency Response Guidebook [15], binoculars and a cellphone. All of these inventory items can be accessed sequentially by pushing the Y Button on the left-hand controller few times, or pushing the B button on the right-hand controller in the similar way.

Book Reading. Since the learners have to consult a book (The Emergency Response Guidebook or ERG, see Fig. 3a) as part of their training, we had to design a usable way to display, browse and read it within the virtual scene. The book itself is part of the inventory for the learner.

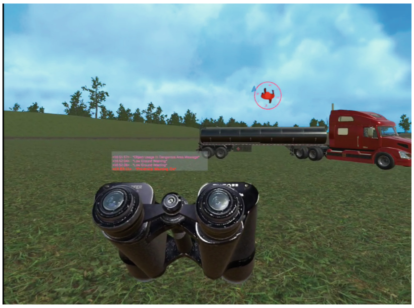
Cellphone. Once called from the inventory, the cellphone can be activated by pulling the index trigger of the left hand controller. A floating dialog box then appear (see Fig. 3b) that allows to report the important information to an emergency call centre (a.k.a. as 9–1–1 centre) for assistance.

(a) Emergency Response Guidebook.

(b) Simulation of a phone conversation with a single or multiple choices selection.

Fig. 3. Inventory items (ERG and Phone).

Binoculars. Once called from the inventory, the binoculars are activated by pushing the index trigger of the left hand controller and then pointed to the scene by changing the orientation of same (left) hand controller. They then display a telescopic view of the part of the scene they are pointed to as illustrated in Figs. 4a and 4b.



(a) Binoculars inventory item.

(b) Binoculars in use.

Fig. 4. Inventory items (Binoculars).

5 System Design

The training scenario consists of a VR simulation of a scene involving a dangerous goods transportation incident. The learner is immersed into VR environment using an HMD and views the environment from a first person perspective as illustrated in Fig. 2. The learner can navigate and explore the scene using handheld input devices (hand controllers). The learner can also access inventory items that can be used during task execution such as ERG reference guide book [15] (see Fig. 3a), binoculars (see Figs. 4a and 4b), and a communication device (cell phone, Fig. 3b).

A formative tutoring system is running at the background to provide the learner with feedback as they navigate the virtual environment. The main task for the initial investigation of the incident scene consists of collecting information about the incident while minimizing risks. As the learner moves in the VR scene, he/she needs to maintain a safe distance from the incident location while remaining uphill and downwind to avoid exposure to fluid or gas leaks. A system of spatial zones monitors entries and exits of areas of relevance for the task. The zones to track and provide instructions include zones for proximity danger, down wind, low ground, and safe viewing distance. The zones can be configured to reflect scenario variations such as the nature of the dangerous material and wind direction. For example, if the learner were to move too close to the incident in the virtual scenario they will receive a warning message shown in their display (see Fig. 5). Formative tutoring system can be used to assess how much support a person needs to complete the scenario; the less support one needs the more autonomous is the learner.

Fig. 5. Warning message displayed.

6 Evaluation Plan

As part of this project, a series of studies will be conducted to evaluate and assess whether the VR training tool increases participants' knowledge of the procedures at the Awareness-level training following a hazardous materials incident. Participants will also be encouraged to provide feedback about any possible improvements that can be made to the VR training tool, its overall design as well as the study protocol. The National Research Council Canada's (NRC) Research Ethics Board has reviewed and approved the project protocol (REB#2021/157). The results of each study will undergo a variety of qualitative and quantitative data analyses. The overall findings from this project will be disseminated as peer-reviewed research articles.

In the first study, we will adopt an exploratory approach where participants' preferences will be examined and their feedback about the VR training tool and VR environment will be obtained through online surveys. The results from the first study will be used to provide guidance on possible improvements of the VR environment that will be adopted in the follow-up studies. The second study will focus on comparing the performance of two different types of users a) novices - people with no former Awareness-level training) and b) experts -people with former Awareness-level training) prior to and following training in VR environment. The third study will focus on comparing two different learning set-ups a) a traditional training scenario (e.g., classroom learning) and b) VR training scenario in virtual environment. Both of these studies will collect feedback on a set of metrics and assess the participants' pre- and post-training performance.

In all studies, participants will complete a set of surveys that will be administered to them during the pre-training, post-training, and at the end of the session. The surveys will collect participants' demographics, as well as the data that will capture their individual differences in terms of immersive tendencies (i.e., the propensity to feel immersed) [17], sense of presence (i.e., the feeling of "being there" in the VR scenario) [14,17], overall workload levels (i.e., the amount of mental and physical effort exerted to complete the scenario) [7], cybersickness (i.e., discomfort or unwanted negative side effects induced by VR) [9], and overall system usability (i.e., the ease-of-use of the system and technology) [1]. Additional performance metrics to assess the participants' performance (such as the overall time to complete the task, number of errors, etc.) will be used specifically in the second and third study. All participants will be asked to provide open-ended feedback about the VR training tool as well as their overall experience at the end of the session.

7 Summary and Conclusions

This paper describes the development of a VR training tool for first responders to enable them to increase their situational awareness and knowledge level for the management of dangerous goods transportation incidents. The requirements analysis conducted with our key stakeholders enabled us to develop a VR system that can adapt and support a variety of use cases and scenarios. The training tool has a formative tutoring system that provides learner with an instant feedback during the navigation in VR. During the next phase of the project, we will focus on developing a robust evaluation plan in which we will conduct the usability evaluation from the user's perspective, as well as the overall software validation in terms of data collection. In addition, we plan to continue with the validation of needs assessments with our key stakeholders. The continuous evaluations during the various stages of development will allow us to propose evidence-based VR guidelines and potential solutions for VR training tools to improve training of first responders in a variety of emergency situations.

References

1. Brooke, J.: SUS-a quick and dirty usability scale. Usability evaluation in industry. CRC Press, Boca Raton, May 1996. https://www.crcpress.com/product/isbn/9780748404605. ISBN: 9780748404605
2. Cook, D.A., et al.: Comparative effectiveness of technology-enhanced simulation versus other instructional methods. Simul. Healthc. J. Soc. Simul. Healthc. **7**(5), 308–320 (2012). https://doi.org/10.1097/SIH.0b013e3182614f95, https://journals.lww.com/01266021-201210000-00006
3. Cooper, N., Millela, F., Cant, I., White, M.D., Meyer, G.: Transfer of training-virtual reality training with augmented multisensory cues improves user experience during training and task performance in the real world. PLOS ONE **16**(3), e0248225 (2021). https://doi.org/10.1371/journal.pone.0248225, https://dx.plos.org/10.1371/journal.pone.0248225
4. Emond, B., Kinateder, M., Cooper, N., Kondratova, I.: Virtual reality for transportation incident management training of first responders in remote areas. In: Interservice/Industry Training, Simulation, and Education Conference, pp. 1–11. National Training and Simulation Association, Orlando, FL (2020)
5. Engelbrecht, H., Lindeman, R.W., Hoermann, S.: A SWOT analysis of the field of virtual reality for firefighter training. Front. Robot. AI **6**, 101 (2019). https://doi.org/10.3389/frobt.2019.00101, https://www.frontiersin.org/article/10.3389/frobt.2019.00101/full
6. Galada, H.C., Gurian, P.L., Hong, T.: First responder knowledge and training needs for bioterrorism. J. Homel. Secur. Emerg. Manag. **10**(2) (2013). https://doi.org/10.1515/jhsem-2012-0064, https://www.degruyter.com/document/doi/10.1515/jhsem-2012-0064/html
7. Hart, S.G.: Nasa-task load index (NASA-TLX); 20 years later. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 50, no. 9, pp. 904–908, October 2006. https://doi.org/10.1177/154193120605000909, http://journals.sagepub.com/doi/10.1177/154193120605000909
8. Kanazawa, A., Hayashi, H.: The analysis of training effects with virtual reality in simple task. In: 2017 6th IIAI International Congress on Advanced Applied Informatics (IIAI-AAI), pp. 345–350. IEEE, July 2017. https://doi.org/10.1109/IIAI-AAI.2017.201
9. Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G.: Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int. J. Aviat. Psychol. **3**(3), 203–220 (1993). https://doi.org/10.1207/s15327108ijap0303, http://www.tandfonline.com/doi/abs/10.1207/s15327108ijap0303
10. Kinateder, M., et al.: The effect of dangerous goods transporters on hazard perception and evacuation behavior - a virtual reality experiment on tunnel emergencies. Fire Saf. J. **78**, 24–30 (2015). https://doi.org/10.1016/j.firesaf.2015.07.002

11. Kinateder, M., et al.: Virtual reality for fire evacuation research. In: 2014 Federated Conference on Computer Science and Information Systems, pp. 313–321. IEEE (2014)
12. LaViola, J.J., Krujiff, E., McMahan, R.P., Bowman, D.A., Poupyrev, I.: 3D User Interfaces - Theory and Practice, 2nd Edn. Addison-Wesley, Boston (2017)
13. National Fire Protection Association: Competency Guidelines for Responders to Incidents of Flammable Liquids in Transport, High-harzard Flammable Trains (2016). https://publications.gc.ca/site/eng/9.812478/publication.html
14. Slater, M., Usoh, M., Steed, A.: Depth of presence in virtual environments. Presence Teleoperators Virtual Environ. **3**(2), 130–144 (1994). https://doi.org/10.1162/pres.1994.3.2.130, https://direct.mit.edu/pvar/article/3/2/130-144/58820
15. Transport Canada: Emergency Response Guidebook (2020). https://tc.canada.ca/en/dangerous-goods/canutec/2020-emergency-response-guidebook
16. Transport Canada: NFPA470: Hazardous Materials/Weapons of Mass Destruction (WMD) Standard for Responders (2022). https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=470
17. Witmer, B.G., Singer, M.J.: Measuring presence in virtual environments: a presence questionnaire. Presence Teleoperators Virtual Environ. **7**(3), 225–240 (1998). https://doi.org/10.1162/105474698565686, https://direct.mit.edu/pvar/article/7/3/225-240/92643