

A design model for 3D desktop virtual environments

B. E. Zayas-Pérez and J. Vázquez-Bustos

Abstract—A model for designing desktop virtual environments is presented. The model considers principles of user-centred design and learner-centred design to integrate a design process that better meets the needs of the learner. The design process is illustrated in the context of prototyping a virtual environment for teaching safety information. Main stages of the design process are described in detail and practical recommendations are given. Design implications derived from evaluation are described in terms of virtual environments usability issues. Results suggest that principles of user-centred design and learner-centred design should be considered as complementary paradigms in order to design usable applications for learning.

Keywords—Desktop virtual environment, learner-centred design, virtual environments design, user-centred design,

I. INTRODUCTION

THE central principle of user-centred design (UCD) is to create usable systems that are easy to learn and use [1]-[4]. This design paradigm aims to facilitate the user's interaction assuming that easier interaction will benefit the learner since the user has more cognitive resource available to concentrate on learning. In contrast, proponents of learner-centred design (LCD) [5]-[7] view the learner's needs as the central aspect of design. In educational and training contexts, LCD can be defined as a development of user-centred design that takes into account the special needs of learners [6]. A learning application must not only have an easy to use interface but it should serve to achieve the learning goal [8], [9]. According to [10], application of heuristics is not sufficient because they fail to address the specific challenge of LCD and the issue of integration usability and learning. [9] suggests the use of instructional design and usability principles to integrate a design process that better meets the needs of the learner. Therefore, premises of UCD and LCD approaches should be considered in assessing educational software in order to ensure usable applications for learning.

In this paper, a model for designing three-dimensional (3D) desk-top virtual environments is presented. The model suggests four main stages: requirements analysis, prototyping,

evaluation and specification requirements or implementation. The model encompasses evaluation as the main part of the design process to assess interactivity and the learner's needs of the learning environment. In this paper, each stage of the model is described in detail along with the application of the model for prototyping a virtual environment (VE) for teaching safety information. The VE was used for research purpose to investigate the elements that contribute for learning and retention of knowledge.

II. DESIGN MODEL

The design model described in this paper comprises four main stages, requirements analysis, design and prototyping, evaluation and specification requirement/implementation. As shown in Figure 1, the first stage of the process is to establish general requirements of the virtual environment in terms of the learner's needs, theoretical frameworks, and technical constrains, which may evolve through the design process. The analysis of requirements helps to establish a baseline to design the instructional content. The output of analysis of requirements will be the input of prototyping stage, where design ideas are developed. This stage involves activities for modelling static and animated components of the virtual environment, developing interactive design of the user-system interface and integrating the instructional content in learning scenarios. Prototypes can be used to support a written requirements specification or the foundation of the implementation stage when an incremental prototype technique is used. Usability evaluations and assessment of the instructional content comprise the evaluation stage. Figure 1 highlights the importance of evaluation through the entire design process.

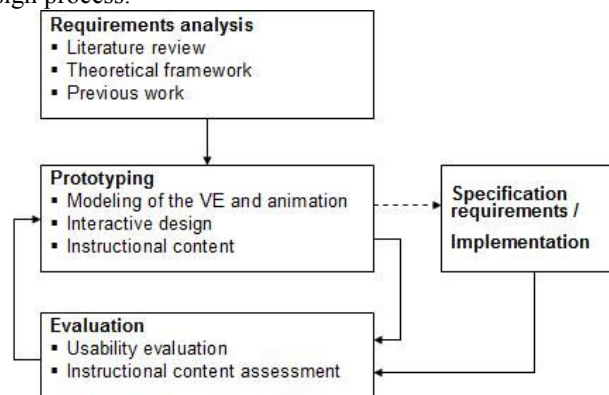


Fig.1 design model for 3D desktop virtual environments.

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B. E. Zayas Pérez is with the Electrical Research Institute, Cuernavaca, Mor. 62490 México (phone: +52-777-3623811; e-mail: zayas@iie-org.mx).

J. Vázquez-Bustos is with the Electrical Research Institute, Cuernavaca, Mor. 62490 México (e-mail: jvasquez@iie.org.mx).

The next sections illustrate how the model was developed at each stage for designing a VE for teaching safety information in a chemistry laboratory.

III. REQUIREMENT ANALYSIS

The first stage of the design process is to establish general requirements of the virtual environment in terms of learning aims. In this phase, theoretical frameworks, approaches and theories that support learning in VEs should be analysed; previous and current research in the domain of VR-based training are valuable source of information. Strengths and weaknesses, and the technological possibilities offered by desktop-virtual reality (VR) technology should also be analysed. These research activities are helpful for envisaging and determining the nature of the design implications, to analyse claims and assumptions in favour of VR-based training and to obtain design ideas from existing research. Design implications derived from this activity included the kind of interaction that should be provided for navigation and object manipulation according to the task demands, forms of representation for the information in the VE and the user-system interface mechanisms.

One of the main tasks in this stage was to gather further information regarding the actual learning environment and how safety training was carried out in a physical setting. It was ascertained that existing safety training consisted of classroom-based instruction for all people that used chemistry laboratories at the beginning of each term. In addition, users of laboratories are required to assess, independently, the risk involved in every experiment they carry out by completing a risk/assessment form.

The design of the learning environment is also determined by the requirements of the instructional content. Hence, the potential scenarios that can be taught, the needs of the instructional design and the capabilities of the desktop-VR technology for delivering learning should be also analysed.

Instructional content information was gleaned from a variety of sources. By reviewing safety literature, safety rules sheets, assisting in a safety induction class and interviewing safety personnel, a number of training scenarios were identified. Training scenarios were categorised into two main groups: laboratory safety precautions and emergency procedures. The former category was intended to be taught in a declarative form. The latter was to allow externalisation of declarative knowledge via students' actions to execute the actual steps of emergency procedures. In laboratory safety precaution scenarios the strategy was to enable students to recognize safety points and to conduct safety inspections in the virtual chemistry laboratory. In emergency procedure scenarios the intention was to recreate situations where the students would have to make decisions in coping with emergencies. For example, deciding on the appropriate actions on hearing the fire bell, or performing the appropriate procedures on discovering a fire in the laboratory.

This activity helps to envisage eleven safety laboratory

precautions scenarios and eight emergency procedures scenarios at the initial design stage in terms of instructions and how to be represented in the teaching environment. For instance, the laboratory precaution scenario *Keep the laboratories and benches tidy*, was designed to depict untidy benches with broken glass. In this scenario, the learner must take actions to (a) tidy up and remove waste material to the appropriate bin, and (b) clear away at once all broken glass and put them into a special receptacle. Similarly, in the emergency procedure scenario *Actions on hearing the fire bell*, the learner must (a) leave the room or area; and then (b) she/he must go to an assembly area (away from the building entrance). These actions involve navigation through the environment to get to the assembly area. The conditions of the environment would be changed in order to test correctness and speed of response. For example, navigation through a smoked-filled area, or the fire escape obstructed by objects.

There were however, seven safety precautions not feasible for implementation because of technical restrictions. Such as those scenarios that involved a high degree of realism to be represented, for instance, colours or smell of chemical materials, or complex manipulation of objects.

A. Physical Environments

Research findings from physical environment for learning are also a valuable source of information for designing VEs. Studies by [11] and [12] have focused on the psychological aspects of physical environments (PEs) for learning, in particular museums. They have identified five aspects that are central to the psychological processes for learning in this type of environment. These are cognitive fatigue, distraction, motivation, emotional affect, and anxiety. Cognitive fatigue refers to the mental effort needed to sustain attention. Concentrating on ambiguous or complex signals, or moving through complicated way-finding paths can contribute to cognitive fatigue in physical environments [11]. In order to reduce cognitive fatigue, a PE must be laid out in a logical manner, so that its organization is easily discernible, supported with appropriate signage to reduce disorientation [12]. Therefore, the VE design should prevent cognitive fatigue by avoid complex-way finding to navigate through the virtual scene. Attributes of the environment that divert attention or distract concentration can inhibit learning; for example, noise and crowded spaces. In VEs both distracters can easily be avoided as the nature of the learning environment can prevent unnecessary sound effects. VEs can also be populated with avatars to provide help to the learner only when required, for instance, to indicate directions or guide instruction. Animation of avatars can be activated in response to actions of the learner or triggered by events in the simulated environment. In this regard, the VE presents textual and auditory information only when the user requests it and objects in training scenarios respond only to learner actions. Visual exposure is defined as the extent to which a person can be seen from different vantage points in a space [11]. People also experience distraction in high visual exposure space when they are located

in large environments with no partitions and barriers. In the case of VE, all information must be confined to one room (a chemistry laboratory), which prevents a visual exposure effect and makes the system a manageable space for learning.

According to [11], control and responsiveness are the concepts that link the PE to motivation and learning. The lack of activity imposed by environmental barriers that restrict movement, or the nature of the learning task in which the learner can be injured can adversely affect learning and cause motivational deficiencies in a PE [11]. They suggest that in order to be more effective in a learning situation, the environment should afford responsive elements that can be manipulated and provide differential feedback. In VEs, learners can act and manipulate their surroundings, explore the environment without the risk of being hurt and receive differential feedback in a number of different modalities. In particular, the VE should allow individuals to freely explore the environment at a self-regulated pace, interactive elements offer visual and aural cues, and responsive events allow users to react to hazardous situations without the risk of being injured. These features provide a sense of control of the system and enhance motivation in a safe environment.

Aspects of PEs that engender cognitive fatigue, distraction, disorientation and decrease motivation may also cause emotional affect and anxiety. For example, untidy and dark spaces, large spaces with high ceilings and long corridors contribute to negative emotional affect. The sense of disorientation produces anxiety [11]. Therefore, [11] claim that 'people feel more comfortable and relaxed in smaller, well-differentiated spaces where they are less visually exposed'. These suggestions can be achieved with a small illuminated room scene.

B. High level requirements

The outcome of the analysis of requirements stage is a list of high level requirements that helps to establish a baseline to design the learning application. For the case of the VE for safety training, the list of requirements embodied the following design implications.

- 1) A training environment which places the learner in a virtual surrogate of the actual chemistry laboratory.
- 2) A desktop virtual environment that not only replicates the physical context but also the conditions in which the learner individually acquires knowledge in authentic scenarios and activities of safety training.
- 3) A virtual environment that fosters strong associations between safety information and relevant objects and scenes in a chemistry laboratory.
- 4) A salient form to present safety information aiming to extend affordance perception beyond the real world constraints.
- 5) A degree of fidelity, verisimilitude and resolution that facilitates affordance perception.
- 6) An interaction and control mechanism that allows active participation and object interaction to acquire declarative knowledge.

- 7) A set of responsive scenarios to promote externalisation of procedural knowledge through users' actions.
- 8) A set of specific requirements in terms of system functionality aimed to support the user tasks including navigation through the environment, object recognition, object manipulation, object location and user orientation.

Although most of the identified scenarios were considered feasible for implementation at this initial stage, subsequent development of the design showed interactive restrictions for accomplishing the implementation.

Having discussed the nature of the problem space, analysed the theoretical basis for the use of VR technology in instructional tools, reviewed previous work about safety training that claimed the putative benefits of desktop VEs, and determined the requirements in general terms, the next step was to explore interaction design ideas in prototypes after selecting the computer tools that would support design and prototyping. The evolution of the instructional content along with the design of the training environment is described in the subsequent sections.

IV. PROTOTYPING

Prototyping stage is to investigate the most suitable representation of teaching scenarios by exploring and testing alternative design ideas through the use of rapid prototypes. Prototypes can convey more information for designers than written specifications [13] and can lead to more effective progress in a poorly specified design than using structured design methods [14], [15]. Low technology prototypes such as drawings, paper-based sketches and storyboards can be used to describe in a graphical form the visual features of the VE and to visualize interactive mechanisms (e.g., menus) in the virtual environment design. This type of prototypes are useful mainly for two-dimensional design, however, to explore design ideas in a three-dimensional space, computer prototypes are needed to create interactive events and animations, to integrate the user-system interface, to represent information in a 3D scene and to determine the limitations of desktop-virtual reality technology. The design of the VE for safety training was conceived as an incremental prototype and implemented with VRML due to its suitability for rapid prototyping and simple development.

A. Modelling of the virtual environment

The modelling of the DVE prototype consisted of two phases. First, an inert scene was modelled. Then, interactive objects and animated scenarios were developed. In the first phase, a 3D representation of an actual chemistry laboratory and some typical laboratory objects and apparatus were modelled. In so doing, the dimensions of the actual chemistry laboratory (including windows and doors) and laboratory equipment (e.g., workbenches, fume cupboards) were preserved. Photographs of the teaching chemistry laboratory were taken and used as the basis for producing a 3D virtual world which reflected, as accurately as possible, the layout and content of an actual chemistry laboratory. Pictures also helped

to provide levels of light, colours and textures of the objects.

The purpose of the second phase was to animate the virtual laboratory and to create specific objects that reacted to the user actions. For instance, at an early design stage, doors that could be opened and objects that could be dragged were modelled. More sophisticated scenarios that involved critical situations addressing emergency scenarios with fire and smoke were also implemented at a later design stage.

V. EVALUATION

The aim of the evaluation is to identify usability problems of the virtual environment and to obtain information about how the learning task is supported. Firstly, heuristic evaluation was conducted and the prototyped was redesigned. Then, formative evaluation was performed to further tested design ideas. Subjective opinions about the learner experience were also collected.

A. Heuristic evaluation

Guidelines for heuristic evaluation proposed by [16] and [17] were reviewed. The taxonomy elaborated by [16] is a characterization of usability issues in VEs, which includes navigation, manipulation of objects, goal selection, fidelity of imagery, input device modes and usage, and interaction metaphors. [17] has suggested twelve guidelines for the design of components and interaction in virtual VEs for a single user. The guidelines apply for VEs that are spatially expansive and populated with a number of objects; VEs that have different points of observation that can be accessed through navigation; and VEs generally modelled on real-world phenomena.

Additional recommendations by [18] were considered for designing virtual scenes and objects. For instance, with respect to design of objects, one guideline reads "Object should be easy to identify or recognize. Individual parts of an object, particularly interactive parts, should also be easy to identify and prominent features of object should be represented. Objects modelled on real world phenomena should be represented accurately and appropriately to match any expectations the user has" (p. 16). The initial consideration from this guideline was that typical chemistry objects should be represented with a high level of detail and realism to make them easy to distinguish and to recognize. Objects should be also located in the VE scene according to their position on the actual chemistry laboratory. These design decisions were further evaluated using observational evaluation by experts in HCI. They used their own knowledge and previous experience with other interaction design. Table 1 shows initial considerations based on guidelines suggested by [16].

B. Formative evaluation

Formative evaluation further assesses and refines evaluation by using representative users in task-based performance scenarios. This was conducted to identify usability problems and assess the design's ability to support task performance, in particular safety inspection, object manipulation and interface control.

Table I early design considerations based on suggestions by [16]

Usability suggestions	Early design considerations
- Design interaction mechanisms and methods to support user performance of serial tasks and task sequences.	- Interaction mechanism should support the user to perform navigation, object interaction and object query via mouse and keyboard interaction. Roaming around for spotting safety violation and perform emergency procedure tasks must be supported.
- Support appropriate types of user navigation (e.g., naive search, primed search, exploration).	- Navigation should be designed to support user exploration via 'walking' metaphor.
- Facilitate user acquisition of survey knowledge (e.g., maintain a consistent spatial layout).	- A small-scale VE should be designed to facilitate survey knowledge and prevent disorientation.
- Provide information so that users can always answer the questions: Where am I now? What is my current attitude and orientation? Where do I want to go? How do I travel there?	
- Use direct manipulation for selections based on spatial attributes (e.g., location, orientation, shape).	- Direct interaction could be used for object manipulation and to interrogate reactive objects.
- When selecting distant objects via direct manipulation, exaggerate object size, appearance, inter-object distances, etc.	- In order to provide visual feedback, objects could increase their size when the mouse pointer is positioned 'over' them.
- Supply users with appropriate selection feedback (e.g., highlighting, outlining, acoustic or verbal confirmation).	- Selection feedback could be provided by highlighting objects. Object manipulation could be supported with a transparent cube 'wrapping' objects to indicate X, Y and Z axis. Alternatively, a mouse pointer could be changed to provide this visual feedback.
- Exploit real-world experience, by mapping desired functionality to everyday items (e.g., clock to convey time).	- Scenarios and object should be represented in a realistic form to exploit perceptual expectancies and natural affordances of the user.
- Use relevant settings that suggest user activity and tasks.	- A realistic representation of the VE could be depicted along with typical objects of a chemistry laboratory.
- Employ rendering techniques that support detailed presentation of setting without introducing lag	- VRML objects with picture-based texture might reduce lag and provide a realistic representation of the VE.
- Pay close attention to the visual, aural, and haptic organization of presentation (e.g., eliminate unnecessary information, minimize overall and local density, group related information, and emphasize information related to user tasks).	- Only objects relevant to training scenarios should be included in the VE.
- Strive to maintain interface consistency across applications.	- The user-system interface and interaction mechanism should be consistent through different scenarios and modules of the training environment.
- Present aural information in a meaningful, timely, and useful manner	- Aural information should be used along with textual information to provide instructional messages. Aural feedback should be used to make the virtual environment more realistic (real sound of burning material, fire alarm, etc.).

For formative evaluation, tasks were designed to assess the functionality and effectiveness of the VE in supporting the user while they performed safety inspections and responded to situations. These issues included understanding of the training scenarios, object location and object identification.

Quantitative and qualitative data were collected using cooperative evaluation [19] involving users and the designer of the VE to identify together usability problems, questionnaires and video-logging of the user-system interactions. As recommended by [19], a set of representative tasks of the virtual environment were selected and performed by users. For this purpose, participants were observed and encouraged to verbalise their impressions in using the VE. Although this technique can be seen as an intrusive method, it was very helpful at prototyping stage for assisting the participants and taking notes of critical incidents.

A critical incident has been defined by [20] as an event that has a significant effect (positive or negative) on the user task performance or user satisfaction with the interface. In addition, quantitative and qualitative measures about navigational behaviour and interaction were obtained by screen recording of the user-system interactions. Furthermore, a questionnaire with closed and opened questions was used to obtain the subjective opinion of participants.

1) Subjects

Fifteen postgraduate students with experience in computer applications were involved in this study. Using novice participants with little experience in using computers would have made the analysis of data more complicated. It was therefore expected that participants with experience in using interactive applications would provide a rich collection of valuable comments and data.

The participants were ten males and five females that voluntarily participated in this study. Ages ranged from 26 to 35 years. They were either self-selected respondents to an e-mail announcing this study or were recruited by direct contact. Their experience in using computers ranged from 10 to 20 years with an average of 13.20 years of experience (SD - standard deviation = 3.23). They were classified into three categories according to their experience in 3D applications: no prior experience (eight subjects), novices (two subjects) and experts (five subjects). Prior experience in a chemistry laboratory was not necessary for this evaluation. However, nine subjects indicated they had worked in a chemistry laboratory with an average of 2.3 years experience (SD = 1.57) while the other six people did not have any familiarity with any chemistry laboratory. Participants were not paid for their participation.

2) Test environment

The usability evaluation was conducted in a room for usability evaluations configured with two desks, one for a workstation and one for recording equipment. Video and audio recording equipment consisted of a VCR, a TV set and a microphone. In order to video-tape the sessions the computer's video signal was multiplexed to the VCR. The VE prototype was installed on a Silicon Graphics O2 workstation running at

120 MHz, with the IRIS operating system, a 21" colour monitor at 1200x800 resolution, 128 MB of RAM and standard desktop input devices (keyboard and mouse).

The Cosmo Player VRML browser was used to present the virtual environment. Cosmo Player is a plug-in to Web browsers that enables users to explore 3D worlds authored in VRML. These 3D worlds might include sound and movies. Cosmo Player offers 'movement controls' and 'examine controls'. The browser was set up for use of only movement controls such as 'tilt', 'go' and 'slide' modes. A guide to Cosmo Player's control functions was placed next to the monitor

3) Experimental tasks

Four representative tasks that embodied all aspects of interaction, navigation issues and task needs were designed as described below:

Task 1. The participants were asked to determine the location of the following objects: two fire exits, two safety showers, a fire extinguisher and a fire blanket. Once objects were located, subjects were instructed to indicate the location of each object in a plan of the laboratory. This task addressed navigation, object location, user orientation, object recognition and fidelity of the VE.

Task 2. The participants were situated in a scenario depicting a shelf to store chemical materials. The task in this scenario was to identify two unlabelled flasks from the shelf and then move them to the nearest workbench. This task addressed object recognition, object interaction, and fidelity of the VE.

Task 3. The participants were asked to navigate through the virtual laboratory and spot seven safety violations. The participants were provided with a piece of paper listing the laboratory safety rules. These were: keep benches tidy; keep all corridors and passages clear; make sure all containers are clearly labelled; no one should smoke, eat or drink; all gas cylinders should be either in a special stand, or chained to ensure that they are safe; safety glasses must be worn where the blue mandatory notice is shown on the door; appropriate safety gear must be worn. This task was not designed to test the participants' knowledge but, rather, to find out if the scenarios were properly represented and easy to understand. The issues addressed in this task were navigation, inspection performance and affordance perception.

Task 4. The participants were situated into a VE scenario depicting a hazardous situation. The scenario showed flasks of flammable material located near a lighted Bunsen burner. The participants' task was to perform emergency procedures to cope with a minor fire. In order to initiate the fire incident, they were asked to click on the virtual Bunsen burner that ignited the chemical material. Then, participants were given ten seconds to put the fire out by using either a fire blanket or a fire extinguisher. After ten seconds from the start of the fire, the fire alarm was activated automatically and the laboratory was gradually filled with smoke. On hearing the fire alarm the participants were instructed to leave the laboratory immediately. The aim of this task was to explore the feasibility

of performing emergency procedures and object manipulation in emergency situations.

4) Usability metrics

Effectiveness in this study related the goals of each task to the accuracy and completeness with which these goals were achieved. This metric was measured for each task by calculating: percent task completion; frequency of critical incidents; frequency of assistance required by the participant to proceed with the task; and the time taken to achieve the task. In particular, task completion was calculated for each task as follows. The number of objects correctly identified (4) and located (6) in the VE was counted in task 1. Participant orientation was measured by counting the number of objects (6) whose correct locations were indicated on a plan of the chemistry laboratory. In task 2 the number of steps to complete the task was calculated. The optimal procedure to achieve this task involved five steps: identification, selection, drag-up, drag-forwards and drag-down. The number of safety violations (7) spotted was measured in task 3. Finally, the number of procedures correctly performed, and the response time, was calculated in task 4. The optimal procedure to achieve this task involved six steps: locate a fire blanket or a fire extinguisher; select either of them; drag the selected object over the fire; move towards the fire exit; open the door; leave the laboratory. User satisfaction was measured by using a subjective rating scale in a questionnaire that included questions about enjoyment, navigation, orientation, object recognition, object location, object manipulation, representation of the environment, presence and appropriateness of the tasks.

5) Procedure

The aims of the study were presented in verbal and written form. They were also told that the study was not to test their abilities to interact with VEs nor their knowledge of laboratory safety but to find out problems in using the application. They were informed that their interaction would be videotaped and that the person conducting the evaluation would be present to assist them and to note down unexpected behaviour and interaction problems. Then, participants were given introductory training using the virtual environment and the Cosmo Player VRML browser. This introductory training consisted of navigation in the virtual laboratory. After practicing for approximately 15 minutes (or the time required for them to feel confident), participants were provided with a sheet of paper describing the tasks to be performed. After they had read the task descriptions participants were asked to carry out four tasks in a limited time of 20 minutes. Object location on the plan of the laboratory was completed immediately after they had finished task 1. When they had finished the four tasks they were asked to complete a questionnaire to collect their subjective opinions about the VE prototype and usability issues.

6) Results

By analysing the video recordings, the comments made in the questionnaire and comments collected during direct observation, a number of usability problems were identified. A user event checklist was developed as an instrument for video

analysis. Events that affected user performance were categorized into five factors such as navigation issues, object interaction, affordance and visual fidelity, browser interface and system performance (see Table II).

Table II critical events of user-system interaction.

Critical events	Score
Navigation issues	72
Object interaction	34
Affordance and visual fidelity	19
Browser interface	41
System performance	24

Usability problems are summarized in relation to navigation, object interaction, affordance perception and subjective rating.

Navigation. It was found that system performance and features of the browser interface affected navigation. For example, jerky movements and lost of navigation control were caused by a poor response to the user's inputs. The system did not process the user's input fast enough, consequently the user was often disoriented and lost control of navigation.

Unclear functionality of the browser menu control was also an element that caused discontinuous navigation, along with the inconsistent responses of the browser. The constant switching between navigation directly on the VE and using the browser menu produced a number of critical negative incidents. Video recordings showed that the user was often confused while trying to select the appropriate roll-over to move forward and backward, turn around or move sideways. There were even participants who tried to perform object manipulation with navigation buttons. Due to these kinds of problems the users expressed frustration and often asked for assistance.

Further comments about navigation issues and the browser interface, disliked participants were expressed in the questionnaire. For example, "*Speed of movement -too fast or too slow; very hard to control the mouse*" and "*Hard to use navigation controls. The go-button which didn't work all the time*". The control panel and roll-over visual feedback were not liked by participants. There was only one comment in favour of the browser interface. This was "*Using the seek-button to move fast to an object*". Due to these kinds of problems the users expressed frustration and often asked for assistance.

It was observed that the restricted field-of-view angle also produced motion problems. The field-of-view determines how much of the environment is visible [21]. Due to this restriction the user was unable to see obstructive objects, which were just below the user's visual angle resulting in a number of user collisions. Other factors that disrupted continuous navigation were unintended activations of interactive objects, i.e., while the user was trying to perform navigation actions with the mouse, animation or interactive objects were very often activated instead.

Video analysis showed that participants used different

strategies for orientation. For example, some people first explored the environment before conducting any task. Others located the fire exit first, so that they knew where to go while performing task 3. It was unclear what objects were used as landmarks for orientation, but even so most participants claimed that they were well orientated and were able to indicate the correct location of objects in the plan of the laboratory (task 1). However, under critical circumstances the participants showed disorientation (task 2). This might happen because of the combination of having an unclear view, loss of navigation control and not being able to manipulate objects under time pressure. In these circumstances people looked for landmarks for orientation, specifically the green sign of the fire exit.

Object interaction. Constraints imposed by conventional input devices such as mouse and keyboard for object manipulation in a three-dimensional space formed one of the main problem categories in completing the evaluation tasks. Moving objects in a direction perpendicular to the view plane without changing the user's position in the VE was difficult. Change of visual perspective was necessary to see the position of objects with respect to other objects. The misjudgement of an object's position in a virtual environment impeded completion of tasks 2 and 4. This task was also difficult to carry out because of the lack of visual feedback. Although the objects in task 2 had the capability of being dragged towards the X, Y, or Z axis, the user could not perceive this feature. Consequently this task was often uncompleted. Further negative comments about object interaction were provided by the participants in the questionnaire or mentioned while they were performing the tasks.

Affordance perception. In assisting the participants while they were doing the tasks, the most recurrent questions were concerned with confirming whether they had correctly recognized various objects. It was clear that some objects were not well represented or modelled such as fire blankets, labelled flasks and fire extinguishers. However, it was also noticed that the lack of familiarity with a chemistry laboratory also caused nonrecognition of objects. For instance, one participant could not identify a fire blanket just because she did not know what it was. Nevertheless, the video recordings showed that participants were generally able to understand the affordances of objects and they recognized scenarios that depicted safety violations. Recognition of interactive objects was facilitated by the visual feedback provided by the VRML browser as the mouse pointer changed in shape when it was placed over this type of object. However, a clash between the style of interaction in real life and in computer applications was observed. Initial attempts to replicate real world affordances in the VE resulted in most of the participants not being able to distinguish which interaction style should be used. For example, nine users attempted to open a door by clicking on any area of the door; however, it was necessary to 'drag' the door from the handle in order to open it. While video recordings indicated that the affordance was perceived, it also

showed that caused frustration and negative comments when the object behaved unnaturally, for instance, the fact that objects did not collide with each other. Comments in favour of the virtual environment included realism of the VE, good representation of scenarios, impressive effects and novelty value.

C. Subjective issue

As mentioned before, participants' subjective opinions regarding their experience in using the VE were obtained from a questionnaire. Table III shows the modal responses which have been calculated from the full set of participants' opinions. Statements 2, 3 and 4 confirmed navigation problems detected in video recordings. Similarly, statements 8 and 9 confirmed the difficulties detected in object interaction. However, statements 2 and 3 indicate that navigation in the VE was easy but unnatural. Users' subjective opinions, in general terms, showed that the VE was enjoyable, easy to learn, well represented, easy but unnatural to navigate and provided a sense of presence and orientation.

There were other factors that affected user performance. These were related to the procedures of the study and to the experimental room. Problems identified that affected user performance were unclear instructions resulting in confusion and distraction from performing the task. For example, in task 2 three participants looked for unlabelled flasks not only in the area of storage shelves, but also in different areas of the laboratory. In the scenario, flasks were only located where the user was situated.

Table III participants' subjective opinion of their VE experience.

	Statements	Modal response
1.	I enjoyed using virtual laboratory.	strongly disagree
2.	Navigation through the environment was difficult.	disagree
3.	I found navigation through the environment natural.	neutral
4.	Navigation is not well-supported by control functions.	agree
5.	I felt well oriented within the environment.	disagree
6.	It was difficult to recognize objects in the environment.	agree
7.	It was easy to locate parts of the environment.	agree
8.	I found the interaction device difficult to manipulate objects.	neutral
9.	I found interaction with the environment natural.	agree
10.	The representation of the whole environment was realistic enough to feel all my senses engaged.	engaged
11.	I did not feel the sensation of 'being' within the environment.	disagree
12.	I would imagine that most people would learn to use the agree system.	agree
13.	The tasks were too long to carry out.	strongly disagree
14.	I found the tasks easy to carry out.	agree

Four subjects verbally commented that the light in the experimental room was too bright which made the screen difficult to see.

These observations were taken into account in later studies. For example, instructions to participants were improved, the amount of information presented was reduced and the length of experimental tasks was adjusted.

VI. DESIGN IMPLICATIONS

Based on results of the formative evaluation, new design ideas were explored and further examined by researchers with experience in HCI. A pilot study of the final version was also conducted with eight chemistry students. The instructional material was also assessed by the person who was responsible for laboratory safety training. His comments and remarks were very valuable from the point of view of an expert in safety training. One of his suggestions was to award points to a student when she or he recognized a safety violation like in video games. However, this approach altered the aims of the learning system since students tended to try for the maximum score with the potential for neglecting 'low scoring' safety information. The following sections summarize the major design decisions made with respect to navigation, object interaction, affordance perception and displaying information as a result of the findings of the formative evaluation.

A. Navigation

System performance and browser user interface. Results of the formative evaluation suggested that certain navigation problems might be avoided both by using a better computer graphical resource to improve system performance, and by avoiding the use of the VRML browser user interface. Hence, VE was migrated to a computer with better graphical resources that markedly improved the response of the system; a DELL Pentium 1.8 GHz desktop PC with a graphic processor 64MB NVIDIA GeForce2 MX/MX 4000. The use of a different VRML browser, also improved navigation. Navigation controls were removed from the browser to encourage direct motion control through the VE, i.e., the user was able to perform navigation actions only through the VE scene.

1) Distractive interactive objects

The VE used in the formative evaluation seemed cluttered with objects and information needed to perform the four evaluation tasks in only one setting; resulting a number of interactive objects unnecessary or irrelevant for specific tasks. The new design of the VE was structured by dividing scenarios into different sessions and only those interactive objects relevant to the task were available. This design decision helped to improve system performance and to avoid over-cluttering the setting, with fewer distracting objects. The function to activate interactive objects was also improved by making them respond to a double click instead of a single one.

2) Restricted field-of-view

The issue relating to the field-of-view [22] was difficult to resolve in the new design of VE. The limited visual area of the VE is due to the physical constraints of the 2D display and the

virtual camera, which restrict the user's ability to use their normal field-of-view for navigation [23]. However, problems derived from this deficiency were less salient with the migration of the VE to a new workstation because of its faster response rate. Obstructive objects were only included when they were relevant to illustrate particular safety regulations. Users were able to recover more quickly from collisions and to overcome obstructive objects more easily in the modified version than in the previous version of VE. An alternative solution for the final design is to provide auditory or visual feedback, when the user collides with objects that are below the visible level of the field-of-view, for example, indicating that an object is blocking the user's way.

B. Object interaction

The original approach in VE interaction was to replicate to the greatest possible degree the performance of the user's task in the real world, since natural interaction should be based on the application goal and tasks [24]. However, some metaphors make the interaction cumbersome and inefficient, which distract learner in performing and learning the task. A more realistic manipulation of objects was suggested to carry out tasks in as intuitive a manner as possible, for example, using 'graspable' objects rather than just 'click-on' objects. In addition, visual feedback was added to interactive objects to facilitate object manipulation. As shown in Figure 2, a translucent cube wrapping the object allowed the user to select the plane towards which she wanted to move the object.

Although the visual feedback was easy to understand, the difficulty of controlling precise movements of objects towards or away from the user, persisted. Given the difficulty most users have with direct manipulation, context-based menus were seen as an alternative approach for user-system interaction. Menus are commonly used to issue commands in 2D graphical user interfaces because they are more effective and precise for some tasks than direct manipulation [24], [27], [28].



Fig. 2 visual feedback for direct manipulation to drag objects in X, Y and Z axis direction.

Usually in this approach a list of possible actions to perform with the object is displayed in a pull-down menu. Having selected the object in the VE, the user could choose what action to perform in a specific context. Menus in DVEs can be located either external to or embedded in the VE scene.

The use of external menus created with Java and Javascript applets were analysed. However, self-evaluation and expert review analysis revealed that the use of menus did not

completely exploit the spatial metaphor and it would be likely that this approach would impede the sensation of 'being' in the VE. Moreover, a technical constraint associated with using a combination of HTML, VRML and applets was that applets have to be displayed separately from the VE or in a pop-up window, which would increase the number of interactive areas. This would result in the user having to negotiate three different areas for interaction: the VE scene, the browser control panel, and interface controls created with applets. It was therefore decided that, for effective LCD, all information would be embedded in the VE.

Embedded VRML-based menus were then designed and evaluated (see Figure 3). Although manipulation of objects through embedded menus represented a good option for performing precise actions, the user was not directly involved in 'doing' the action and a number of sub-actions were necessary to perform even a simple task. Consequently scenarios involving complex manoeuvres with objects were excluded from VE and object interaction was reduced to a single action. The results of this analysis provided valuable insights for presenting embedded safety information in the final design of VE. It also helped to narrow the number of safety scenarios and to distinguish which of them could be taught in declarative or procedural form. Although this decision seems drastic, it was based upon offering the simplest interactivity to the learner. Further studies are needed to address the issue of the differences in effectiveness between symbolic interaction through menus (either external to the VE or embedded in the VE), and direct manipulation.

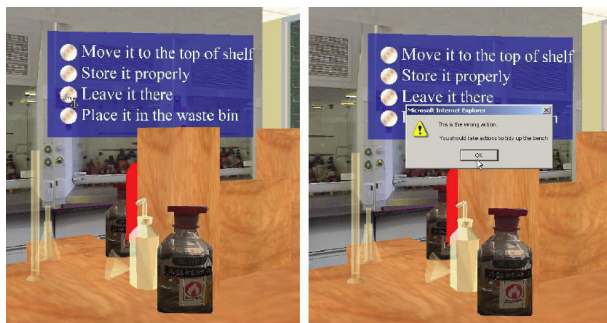


Fig. 3 Exploring symbolic manipulation through the use of embedded menus.

C. Affordances

Objects affordances are intrinsically related to their realistic representations (functional and visual) in the VE. To enhance graphical representation, objects were textured with image files obtained from photographs of real objects, instead of shades of colours. In order to enable rapid identification, objects were highlighted by altering their size when the mouse pointer was pointing to the object (see Figure 4). With respect to unnatural behaviour of 'floating' objects, simulated 'gravity' was added. However, it was not possible to avoid the unnatural behaviour which resulted in objects appearing to go 'through' each other since object-to-object collision detection is not supported by VRML browser.



Fig. 4 a better visual representation of virtual object was achieved using images file textures.

D. Displaying embedded information

Similar to the technique used by [25] who utilized embedded symbolic information to display annotation in an immersive virtual environment, textual and auditory explanations were used to deliver semantic safety information about laboratory objects and scenes on panels. Short sentences explain laboratory precautions associated with typical laboratory objects or scenes. Further information can be heard by playing the audio clips in the panel. This combination allows the system to provide abundant information while reducing user fatigue from reading long passages. According to [25], one of the advantages of audio is that it allows the user to keep the visual channel open while receiving aural information. Some panels include images to provide pictorial details about objects that cannot be easily perceived in the VE or when it would be tedious to read a long textual description or listen to an extensive narration (see Figure 5). Various techniques were explored to present information within the environment. For example, displaying or playing annotations when the user was approaching a particular object; or clicking on a distinct marker such as '!' around the laboratory. However, these design ideas did not successfully indicate a clear link between objects and information. In order to make the relationship between objects and pertinent safety information closer, it was decided that annotations would exhibited near the spatial location of objects within the environment. Unlike the technique used by [25] where annotations were always visually present in the environment, panels in the VE become visible solely when the user clicked on objects.



Fig. 5 embedded panels provide textual, auditory and pictorial information.

VII. LEARNING RESULTS OF THE VE

The final version of the VE depicts a highly realistic representation of an actual chemistry laboratory. It offers a contextual environment to learn about laboratory precautions; the opportunity to practice responses to emergency situations; and a useful tool for researching the teaching and learning of laboratory safety knowledge. In order to prevent interaction problems from impeding learning, the VE design was kept as simple as possible. The learner activity in the VE was reduced to two simple user actions: the freedom-to-roam inside the VE and a single click to interact with objects or to obtain information. All safety information was confined to a single room to make the system a manageable space for learning. Training scenarios were divided into four sequential instructional sessions that were integrated in an HTML web page. An overview of the system and a brief training session for getting familiar with the VE are presented at the beginning of training. The four instructional sessions are *Knowing the lab*, *Laboratory precautions*, *Emergency procedures* and *Quiz questions*.

The VE was used as experimental platform to study the effects of information location and interactivity on learning laboratory safety precautions and emergency procedures. The term 'information location' is concerned with the spatial relationship between linguistic information (text and audio) and virtual reality objects. 'Interactivity' refers to the actions by the learner that are afforded by the virtual environment to perform object manipulation, navigation and user-system interaction. Figure 6 shows the test scores of four experimental groups (48 students) that participated in the empirical study for learning and retention of knowledge of laboratory safety precautions knowledge using the VE.

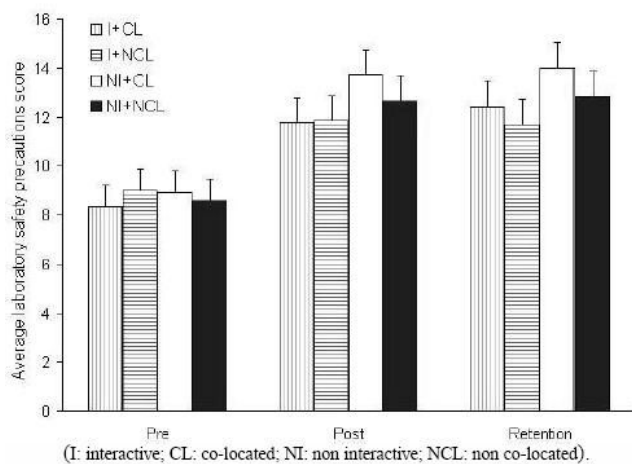


Fig. 6 summary of average test score results for laboratory safety precautions knowledge.

VIII. CONCLUSION

This paper presents a design model for 3D desktop virtual environments. A detail description of each stage was presented in the context of prototyping a VE for teaching safety information. Various design ideas were explored and evaluated

through the use of conventional human-computer interaction methods, incremental prototype technique and assessment of the instructional content. The evaluation revealed that the most important usability problems are associated with navigation, object manipulation and interaction that affected the learning goal. Design decisions considered premise of both approaches, UCD and LCD. An example of a salient design decision was related to interactivity. It can be seen that the 'optimal' level of interactivity that prevents detriment to learning is to keep object manipulation as simple as possible for task performance. Therefore, in the case of the VE object interaction was minimized to a single mouse click on objects for retrieving information and operating objects. In operating objects the system should provide support to perform mundane actions that do not contribute greatly to the enactment of doing by performing 'automatic' actions. For instance, in training how to extinguish a small fire when risk is not involved, the student may have to reflect on what type of extinguishing media is the most effective according to the type of fire; once a fire extinguisher has been 'grasped' or just selected, for example, the user can then click on the base of the fire and the system 'automatically' operates the fire extinguisher to put the fire out. It seems to be that 'doing' at this level of abstraction would be more effective than integrating complex manipulation to perform tasks as in the real world. Easier interaction might be effective for task performance but might not always be effective for learning or problem solving. It can be concluded that UCD and LCD are not mutually exclusive but provide complementary paradigms for VE interface design.

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- B. E. Zayas-Pérez** BSc in computer sciences (1990) from Puebla Autonomous University (México). He obtained his MSc in human-centred computer systems (1995) and PhD in computer sciences (2005) from Sussex University, U.K..
He is currently at the Monitoring Process Department of the Electrical Research Institute at México. He is leader project related to the application CAD and virtual reality for the electric industry. His research interest includes human-computer interaction and virtual reality environments for learning and training. Dr. Zayas is member of IEEE computer Society.
- J. Vázquez-Bustos** He holds a Bachelor's Degree in Electronic Engineering awarded at the Instituto Tecnológico de la Laguna (Mexico) in 1994, and a Master in Science (Eng.) in Data Communications awarded at the University of Sheffield (England) in 2000.
He works for the Instituto de Investigaciones Electricas (Electrical Research Institute) in Cuernavaca, Morelos, Mexico since 1994, where he has been involved in several engineering projects mainly in the fields of electronics, communications and computer systems. He has designed and developed human-machine interfaces, distributed computer systems and real-time data acquisition systems. He has been consultant for several national companies in the oil and power-generation sectors. Recently he has been project leader in several projects involving the use and integration of 3D modeling and CAD software. He has extensive knowledge of several RDBMS and CAD software systems and his main areas of professional interest are: data acquisition systems, software engineering, internet technologies, and digital communications.
- This author became Senior Member of the Institute of Electrical and Electronics Engineers, Inc. (IEEE) in 2006, and currently he is chair of the communications chapter in Mexico's IEEE Morelos Section.